Unconventional Micro-Manufacturing and Integration Technologies

Frank Niklaus

Outline

- Background
- Micro-Manufacturing and Integration Research
  - Heterogeneous 3D Integration for MEMS & NEMS
  - Integration and Packaging for MEMS
  - Nanofabrication Technologies and Graphene NEMS
- Summary

KTH Royal Institute of Technology

Sweden's largest technical university:

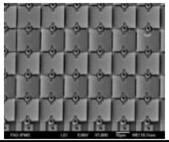
- More than 13,000 full-time students.
- Close to 1,800 research students.
- Around 3,500 full-time positions.

Department of Micro- and Nanosystems

Head: Prof. Göran Stemme

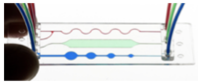
- **Micro and Nanosystem Integration**

  Prof. Frank Niklaus



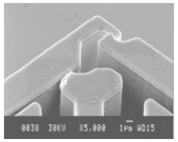
- **Lab-on-a-Chip and Polymer Devices**

  Prof. Wouter van der Wijngaart



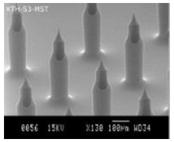
- **Microwave and THz MEMS**

  Prof. Joachim Oberhammer



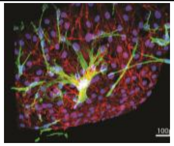
- **Biomedical Devices**

  Assoc. Prof. Niclas Roxhed



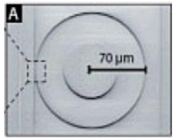
- **Bioelectric Hybrid Systems**

  Ass. Prof. Anna Herland



- **Photonic MEMS**

  Ass. Prof. Kristinn Gylfason



Thanks to all Colleagues at KTH !

Support

- Erika Appel — Admin. Ass.
- Ulrika Pettersson — Admin. Ass.
- Mikael Bergqvist — Technician
- Cecilia Aronsson — Technician

Researchers

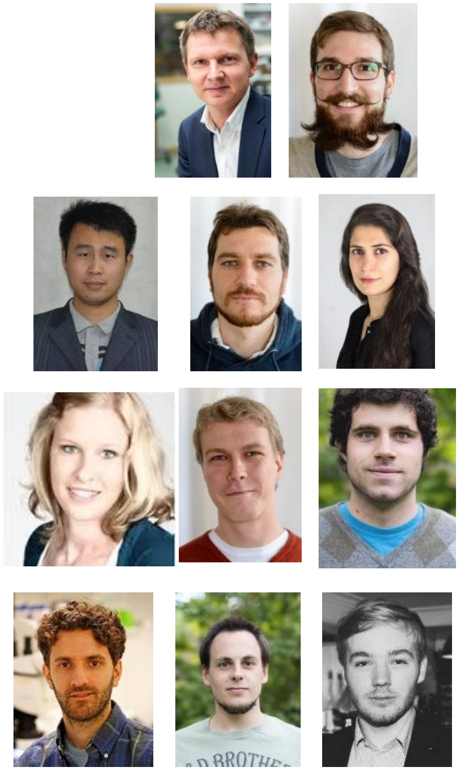
- Göran Stemme — Prof.
- Wouter van der Wijngaart — Prof.
- Joachim Oberhammer — Prof.
- Niclas Roxhed — Assoc. Prof.
- Kristinn B. Gylfason — Assis. Prof.
- Anna Herland — Assis.Prof.
- Hans Sohlström — Assoc. Prof.
- Tommy Haraldsson — Researcher
- Ilya Anoshkin — Researcher
- Oleksandr Glubokov — Researcher
- Jonas Hansson — Researcher
- Petr Makhalov — Researcher
- Umer Shah — Researcher
- Simon Bleiker — Researcher

PhD Students

- Gabriel Lenk
- Floria Ottonello Briano
- Simone Pagliano
- Arne Quellmalz
- Mina Rajabi
- Federico Ribet
- Stephan Schröder
- Serguei Smirnov
- Fritzi Töpfer
- Alexander Vastesson
- Xiaojing Wang
- Reza Zandi Shafagh
- Zhou Xiamo
- Zhao Xinghai
- James Campion
- Valentin Dubois
- Alessandro Enrico
- Xuge Fan
- Jessica Liljeholm
- Linnea Gustafsson
- Maoxiang Guo
- Weijin Guo
- Carlos Errando Herranz
- Emre Iseri
- Staffan Johansson
- Aleksandr Krivovitca
- Laila Ladhani
- Miku Laakso
- Torben Last

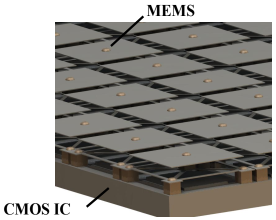
Micro and Nanosystem Integration Group

- 8 Ph.D. students at MST
- 2 industrial Ph.D. students at SenseAir and Silex Microsystems
- 1 postdoc and 3 contributing senior researchers

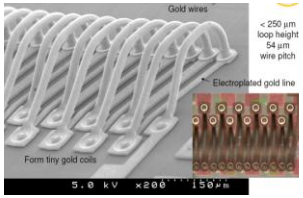


Four Research Topics

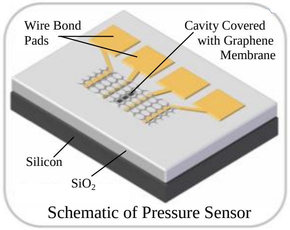
- **Heterogeneous 3D Integration Technologies for MEMS and NEMS**



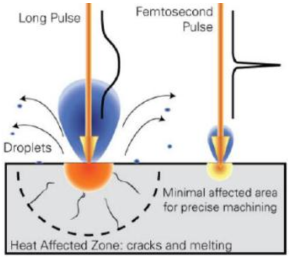
- **Integration and Packaging for MEMS**



- **Nanofabrication Technologies and Graphene-Based NEMS**

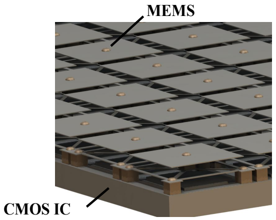


- **Femotosecond Laser-Based Micromachining for MEMS & NEMS**



Research Topics in Group

- **Heterogeneous 3D Integration for MEMS & NEMS**



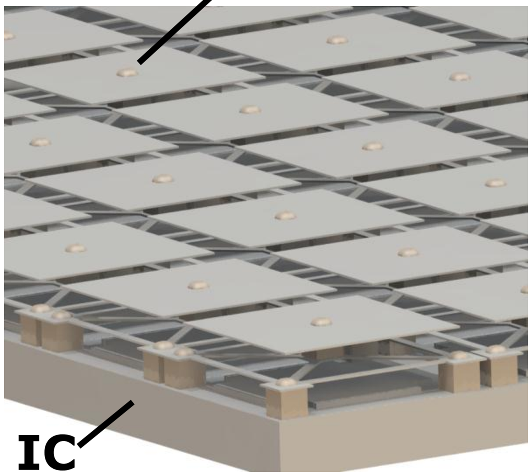
- **Integration and Packaging for MEMS**

- **Nanomanufacturing Technologies and Graphene NEMS**

Heterogeneous 3D Integration for MEMS & NEMS

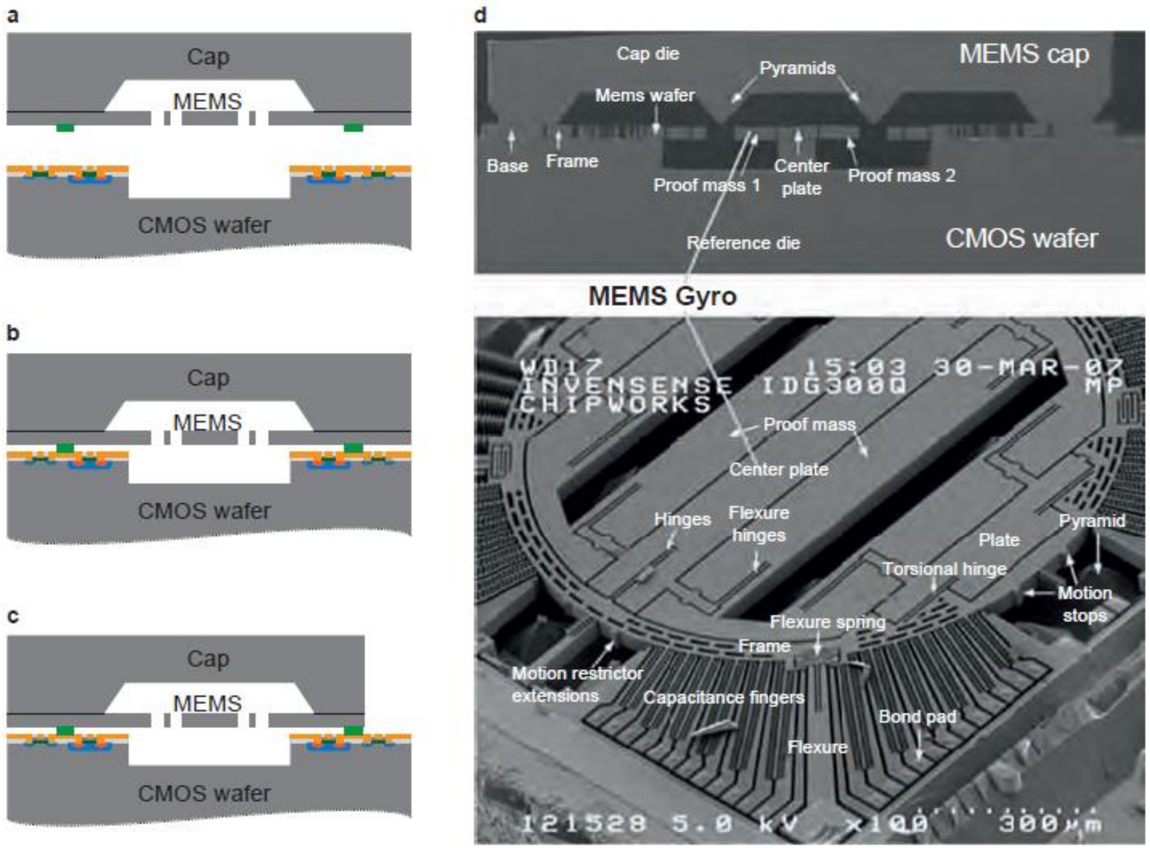
Motivation

- New MEMS designs, functionalities and material combinations.
- High performance MEMS materials on standard foundry ICs.
- Very high integration densities for smaller and cheaper components.

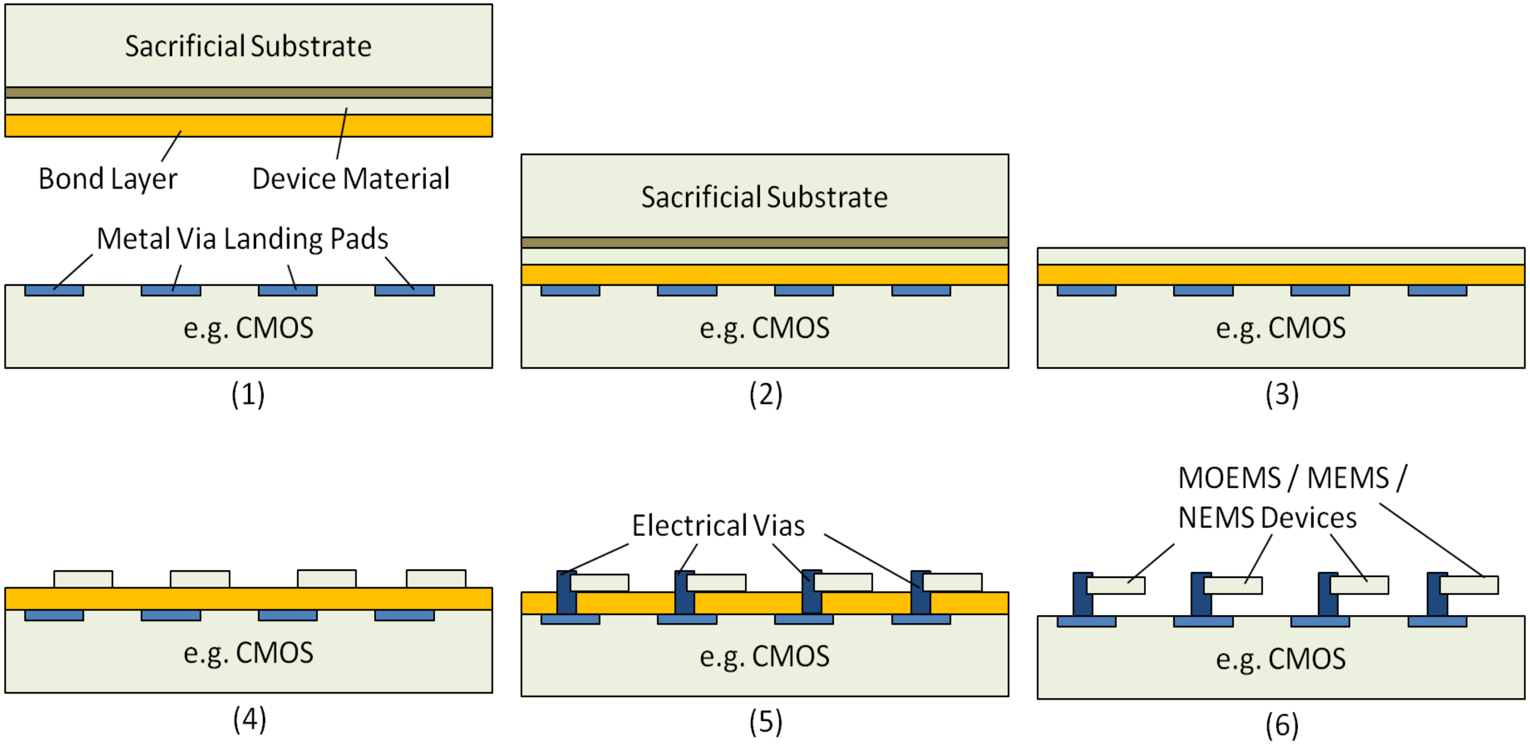


3D Integrated MEMS on ICs

Commercial Examples: Invensense (gyro), mCube (accel.)



Via-Last Heterogeneous 3D Integration Platform

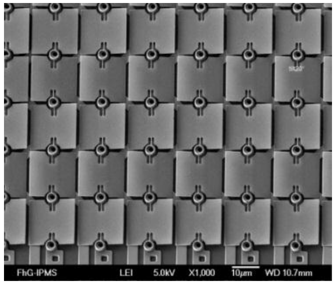


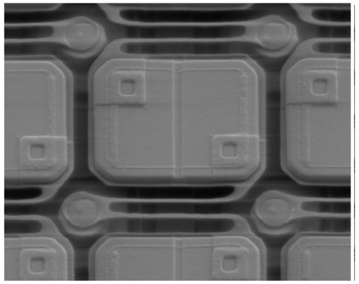
Advantages

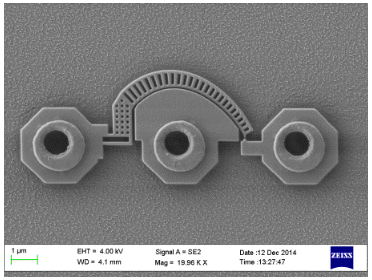
- No wafer-to-wafer alignment.
- Extreme reduction of via and dimensions (sub µm) possible.

Implemented Applications

- Si Micromirror Arrays
- IR Bolometer Arrays
- NEM Relays

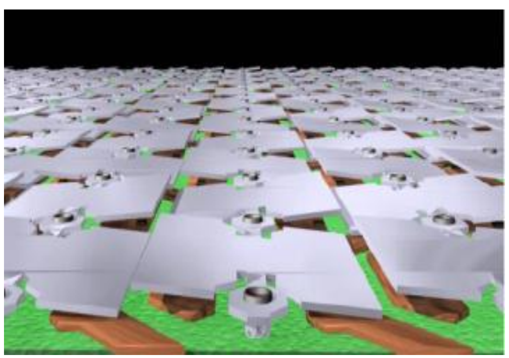




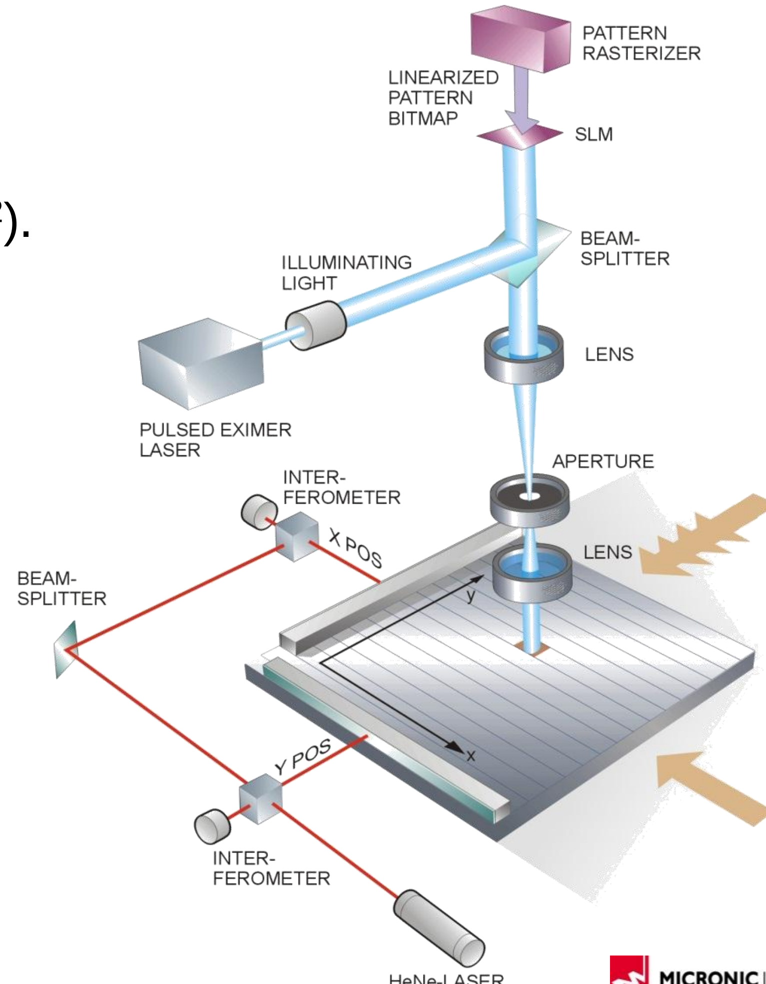


Tilting Micro-Mirror Arrays (SLMs) for Maskless DUV Lithography Systems

- Step and repeat maskless lithography.
- 1 million mirrors (mirror size 16 x 16 μm^2).
- Single mirror actuation with underlying CMOS.
- Analogue tilt actuation in 16 steps (gray-tones) possible.

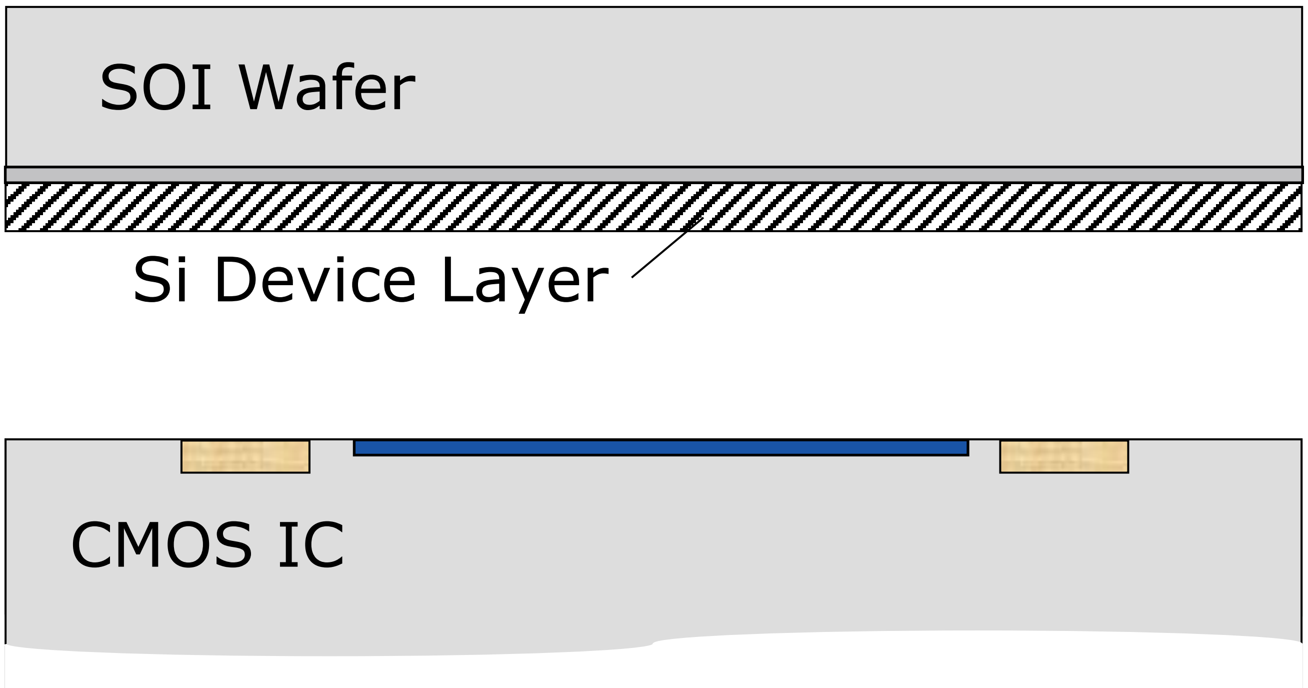


Source: Zimmer, Fraunhofer IPMS

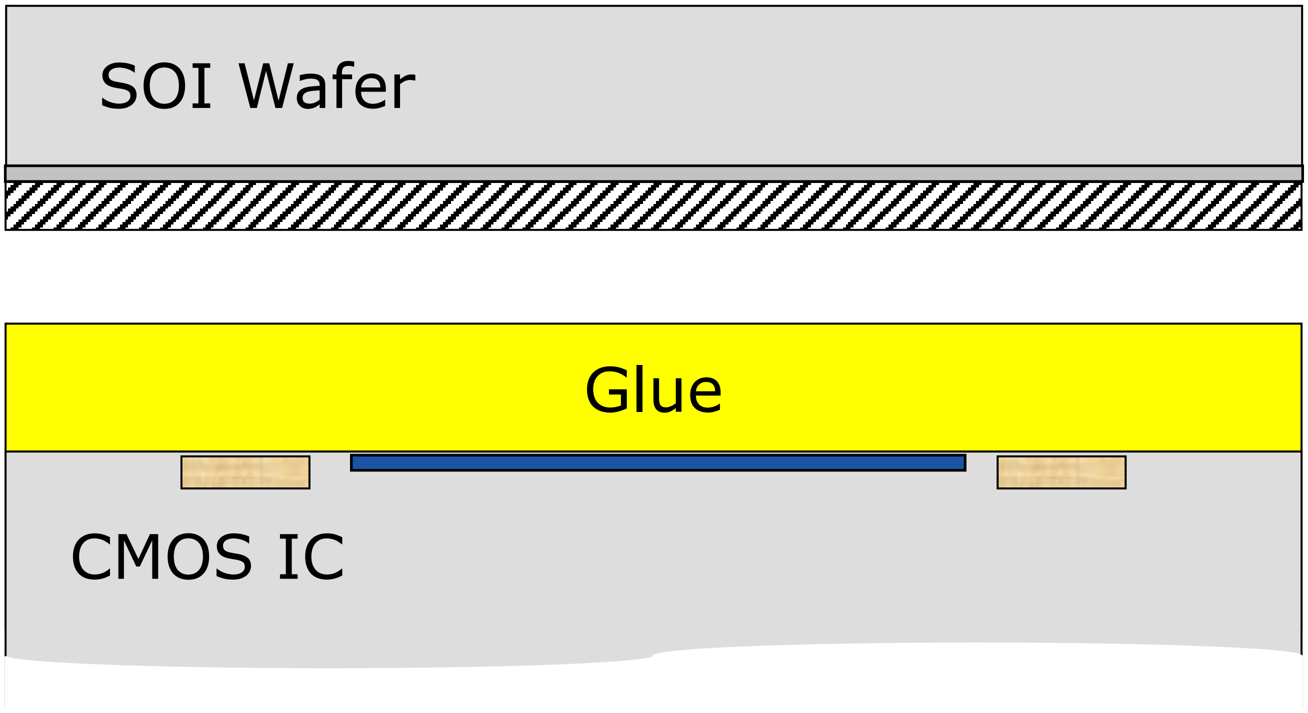


MICRONIC LASER SYSTEMS

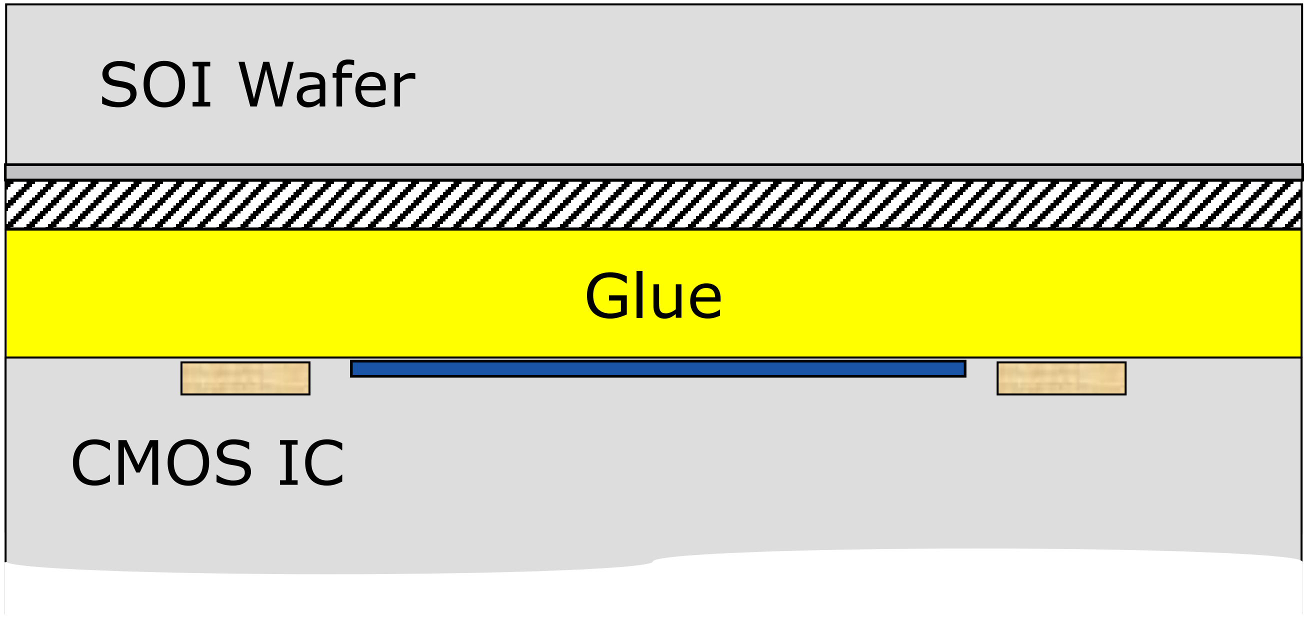
Via-Last Heterogeneous Integration for Mono-Crystalline Si Mirrors on CMOS



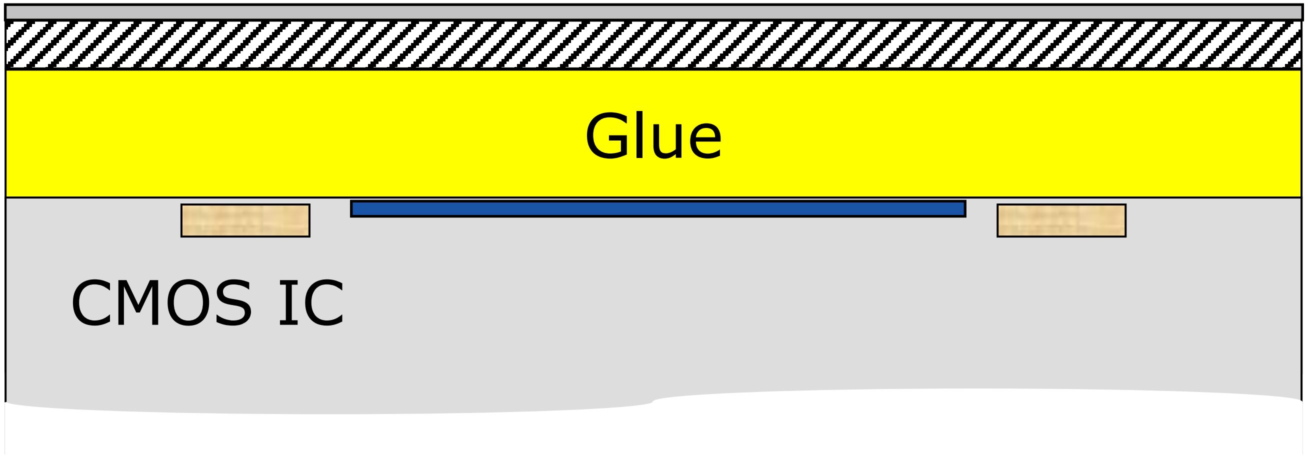
Si Mirror Integration: Dispense Glue



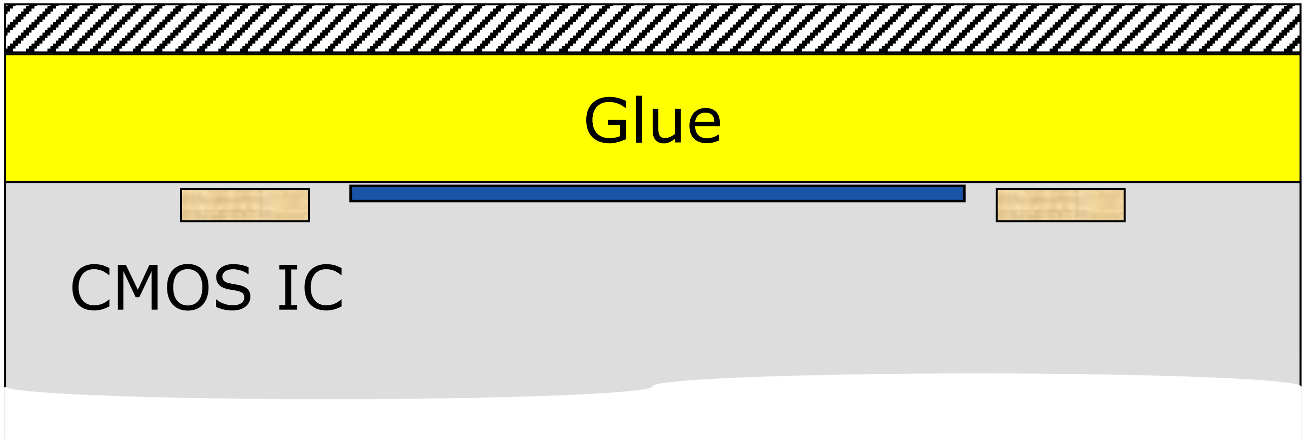
Si Mirror Integration: Adhesive Wafer Bonding



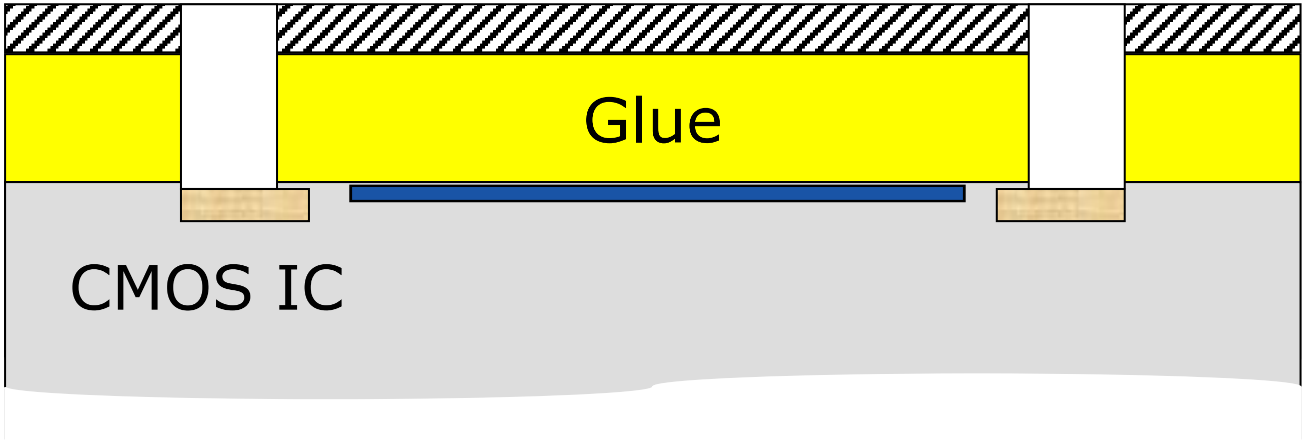
Si Mirror Integration: Sacrificial Wafer Thinning



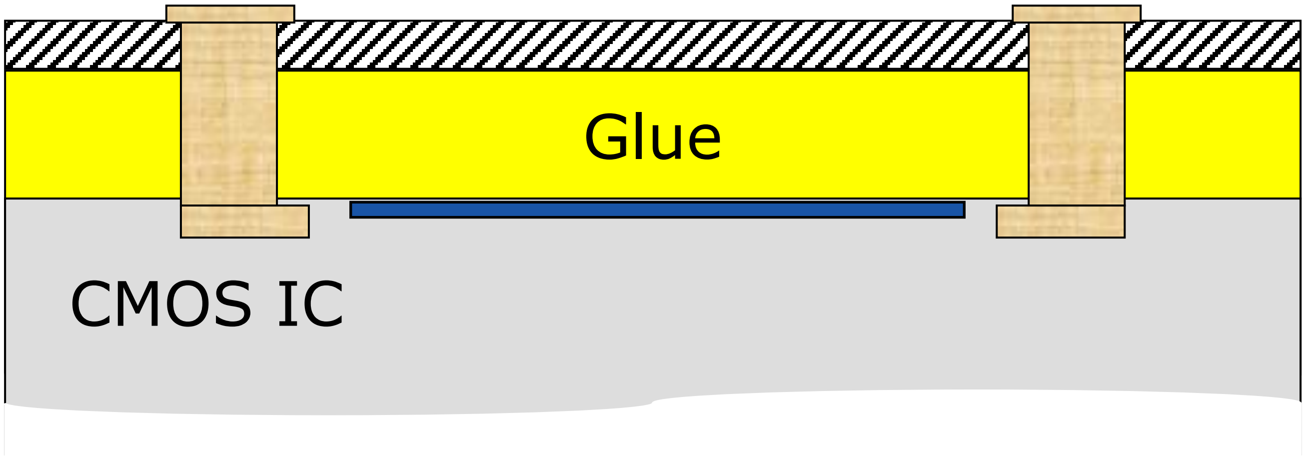
Si Mirror Integration: Removal of SiO_2 Etch-Stop



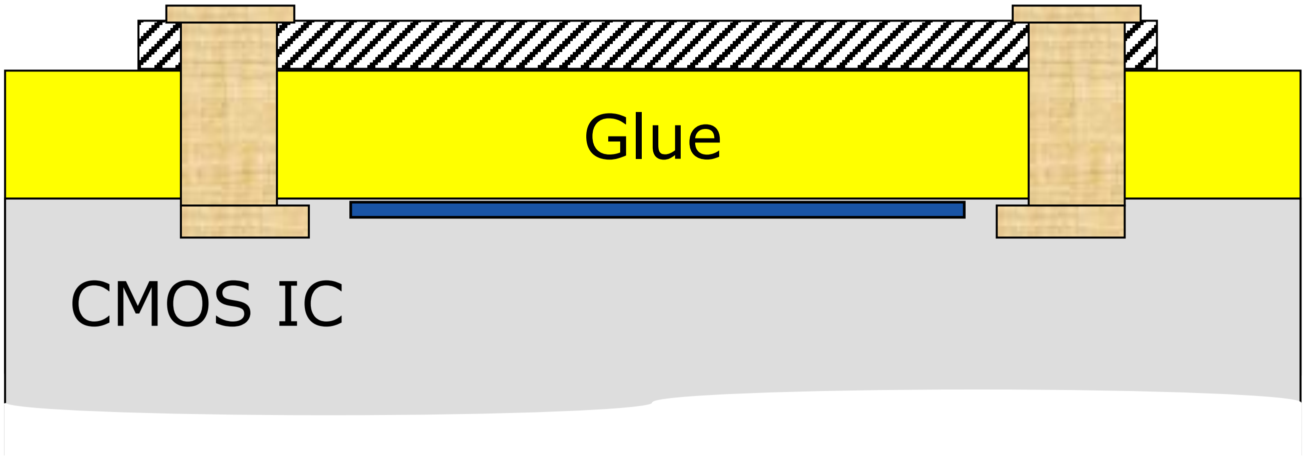
Si Mirror Integration: Via Etch



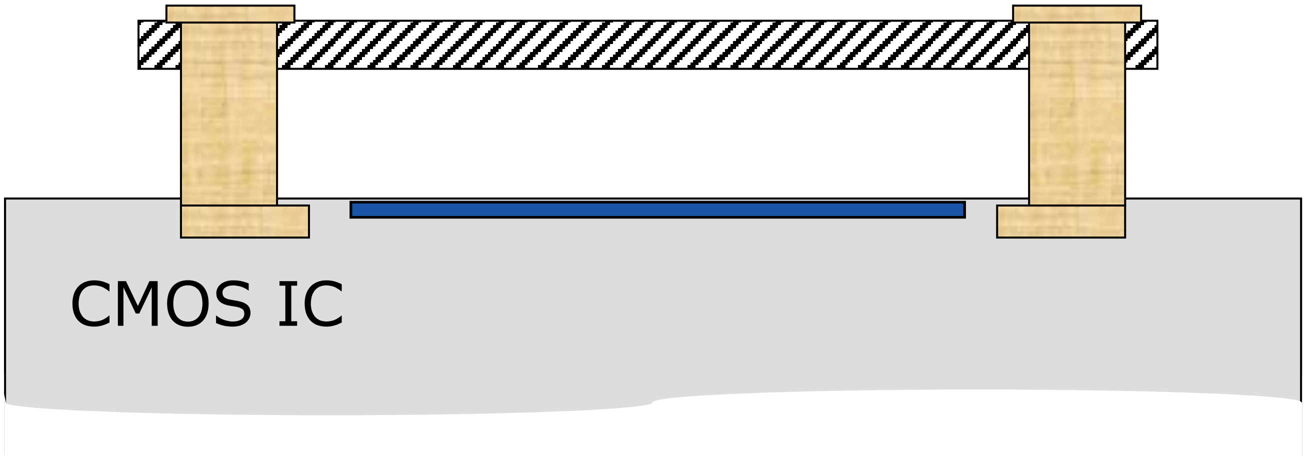
Si Mirror Integration: Via Formation



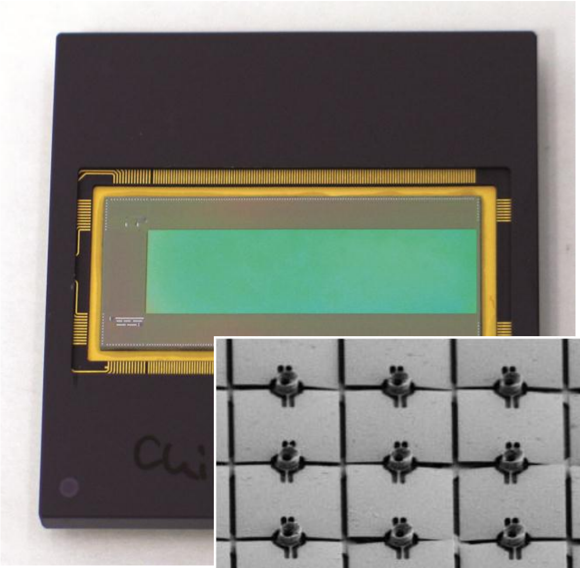
Si Mirror Integration: Mirror Formation

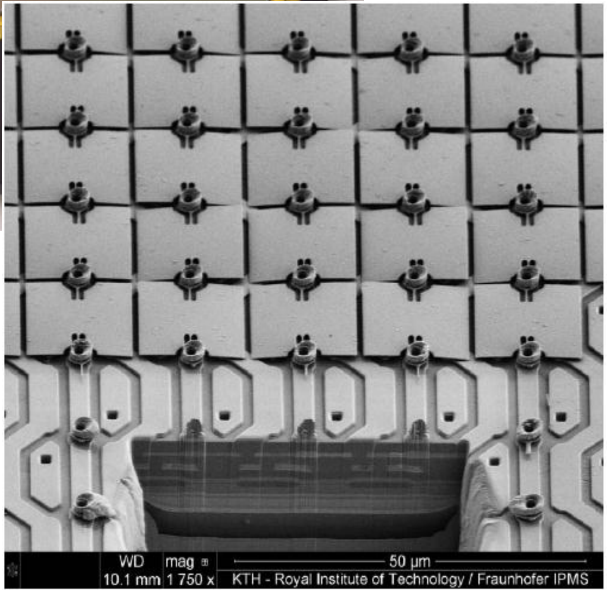


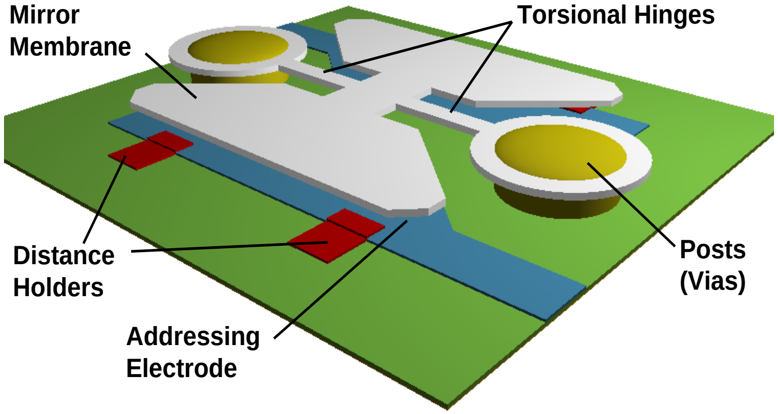
Si Mirror Integration: Mirror Release

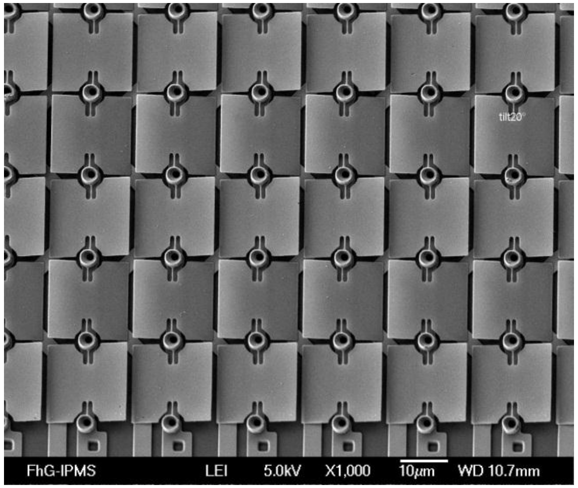


1 M-pixel Mono-Si Mirror Array on CMOS





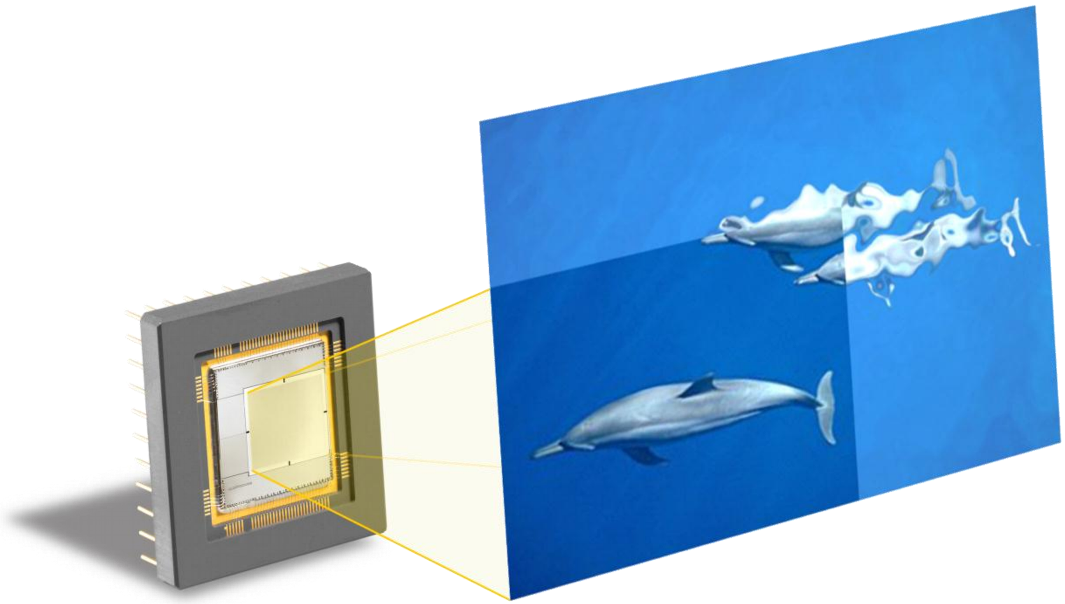


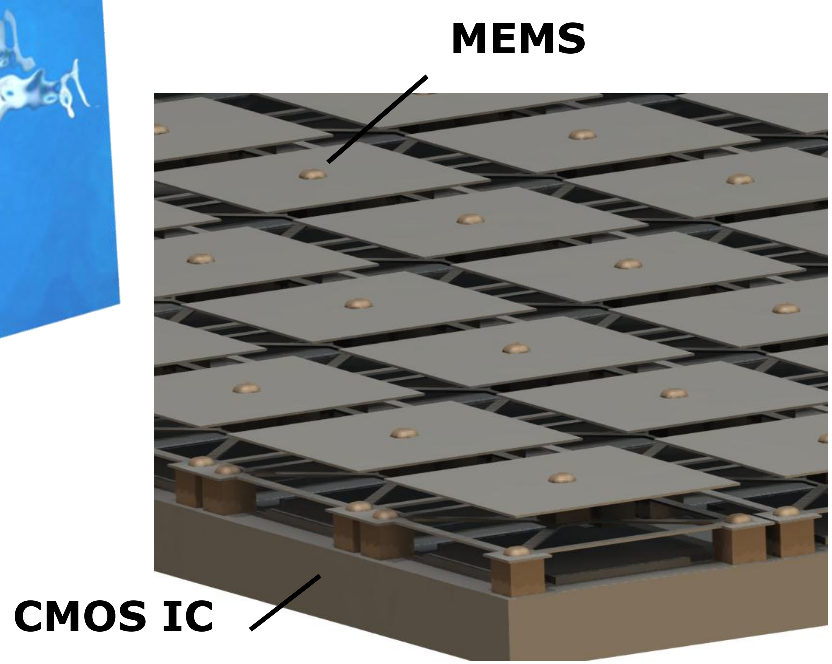


Zimmer, Lapisa to appear MEMS 2011

SLMs for Adaptive Optics in Astronomy and Microscopy

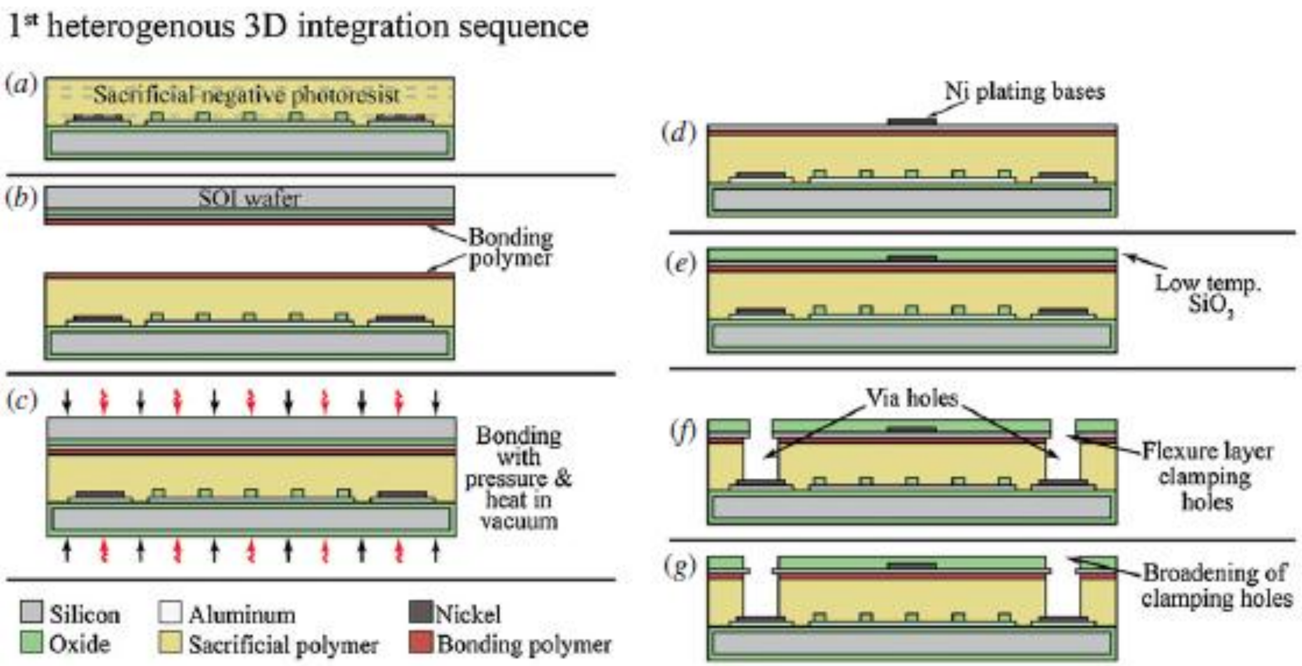
Wave-front correction using piston-type mirror arrays





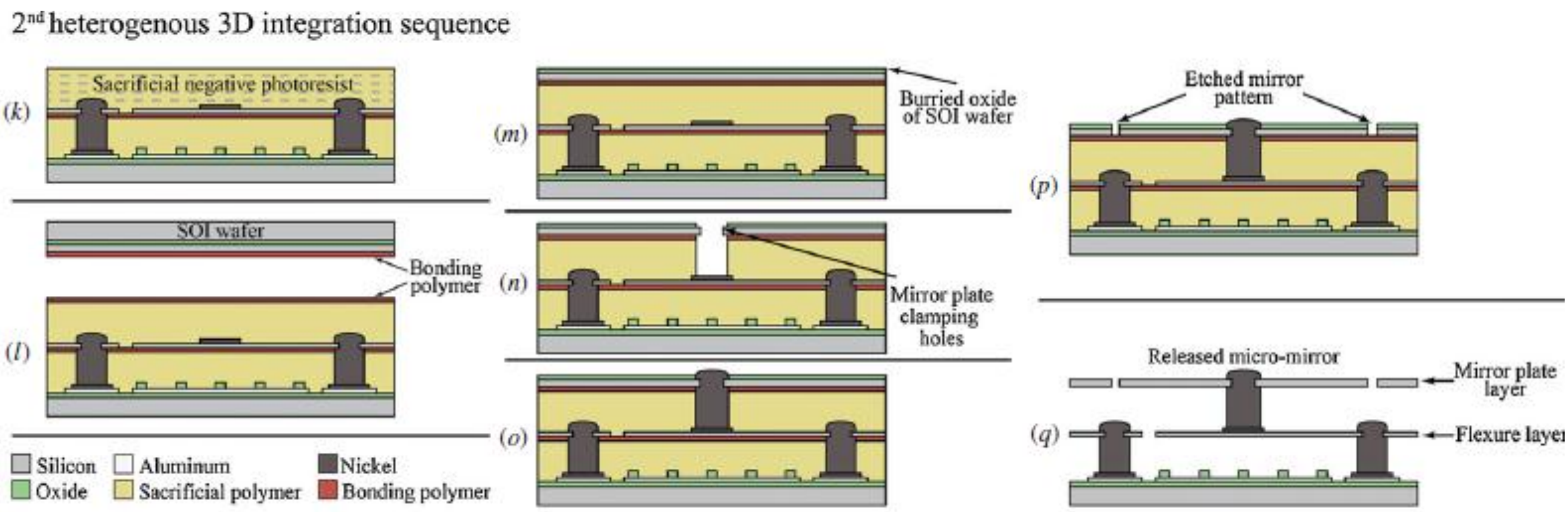
Source: Lapisa, KTH and Zimmer, Fraunhofer IPMS

2-Layer SLMs Fabrication Process



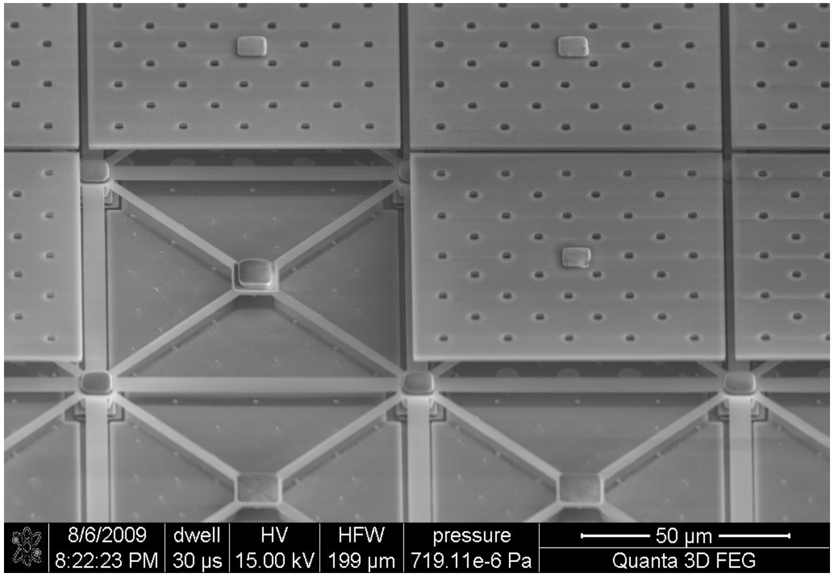
Lapisa, M., Zimmer, F., Stemme, G., Gehner, A., & Niklaus, F. (2013). Heterogeneous 3D integration of hidden hinge micromirror arrays consisting of two layers of monocrystalline silicon. *Journal of Micromechanics and Microengineering*, *23*(7), 075003.

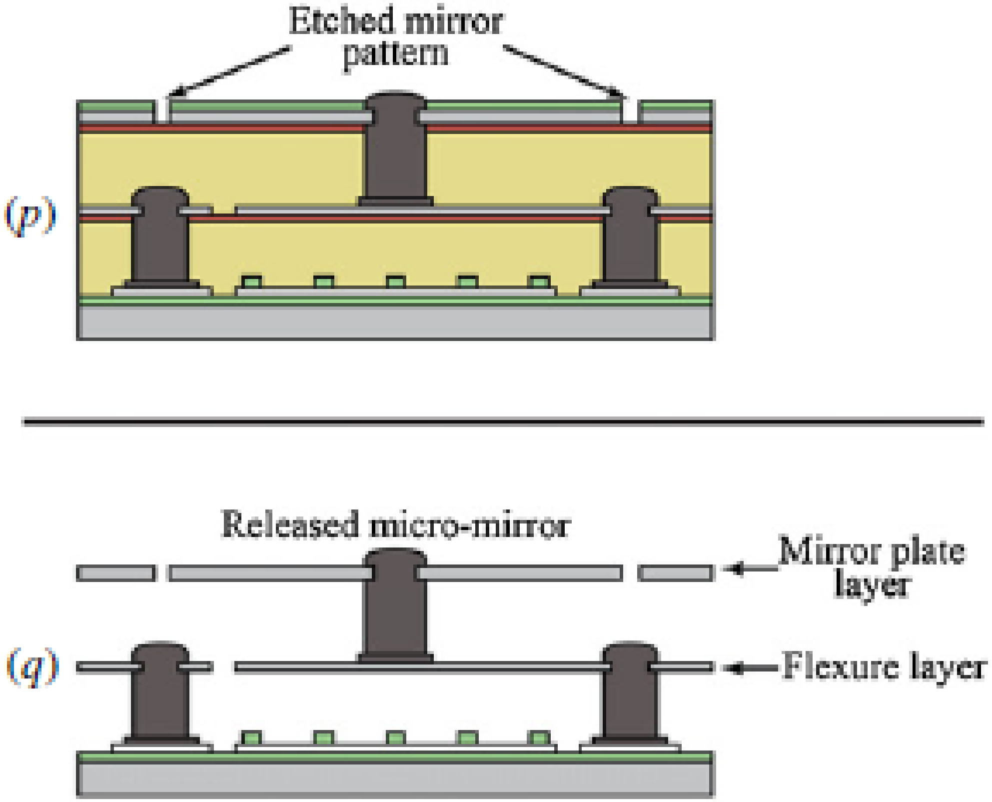
2-Layer SLMs Fabrication Process



Lapisa, M., Zimmer, F., Stemme, G., Gehner, A., & Niklaus, F. (2013). Heterogeneous 3D integration of hidden hinge micromirror arrays consisting of two layers of monocrystalline silicon. *Journal of Micromechanics and Microengineering*, *23*(7), 075003.

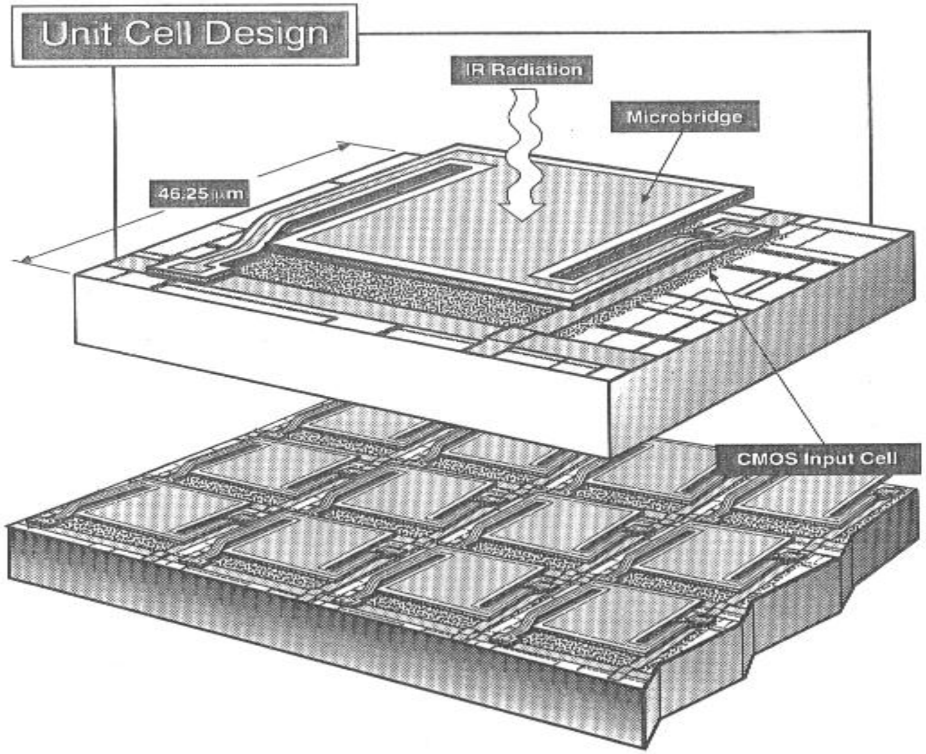
Via-Last Heterogeneous Integration for Piston-Mirrors Using Two-Step Layer Transfer

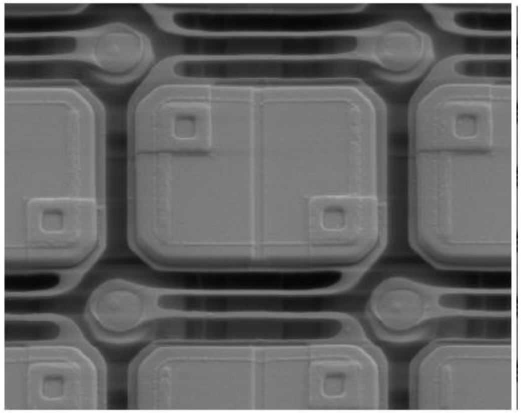




Lapisa, M., Zimmer, F., Stemme, G., Gehner, A., & Niklaus, F. (2013). Heterogeneous 3D integration of hidden hinge micromirror arrays consisting of two layers of monocrystalline silicon. *Journal of Micromechanics and Microengineering*, *23*(7), 075003.

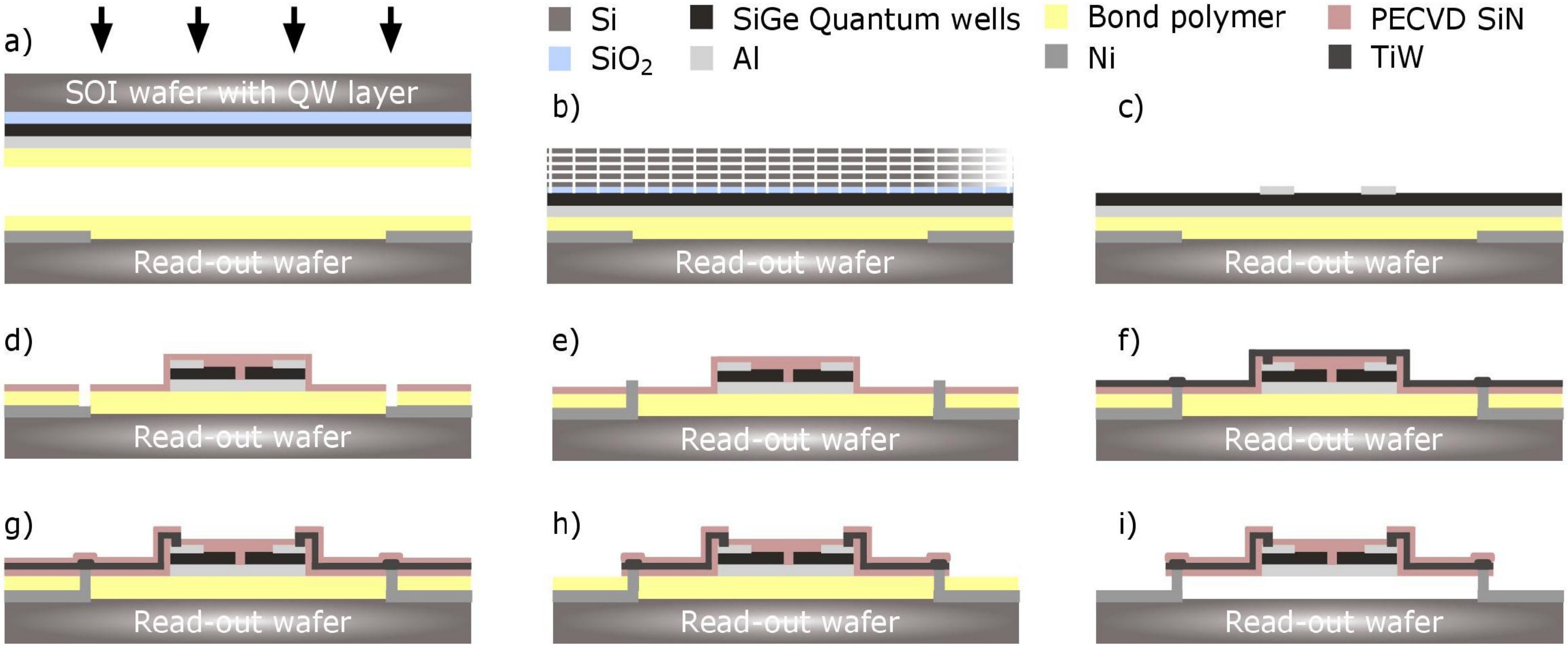
Bolometer Array for IR Imaging





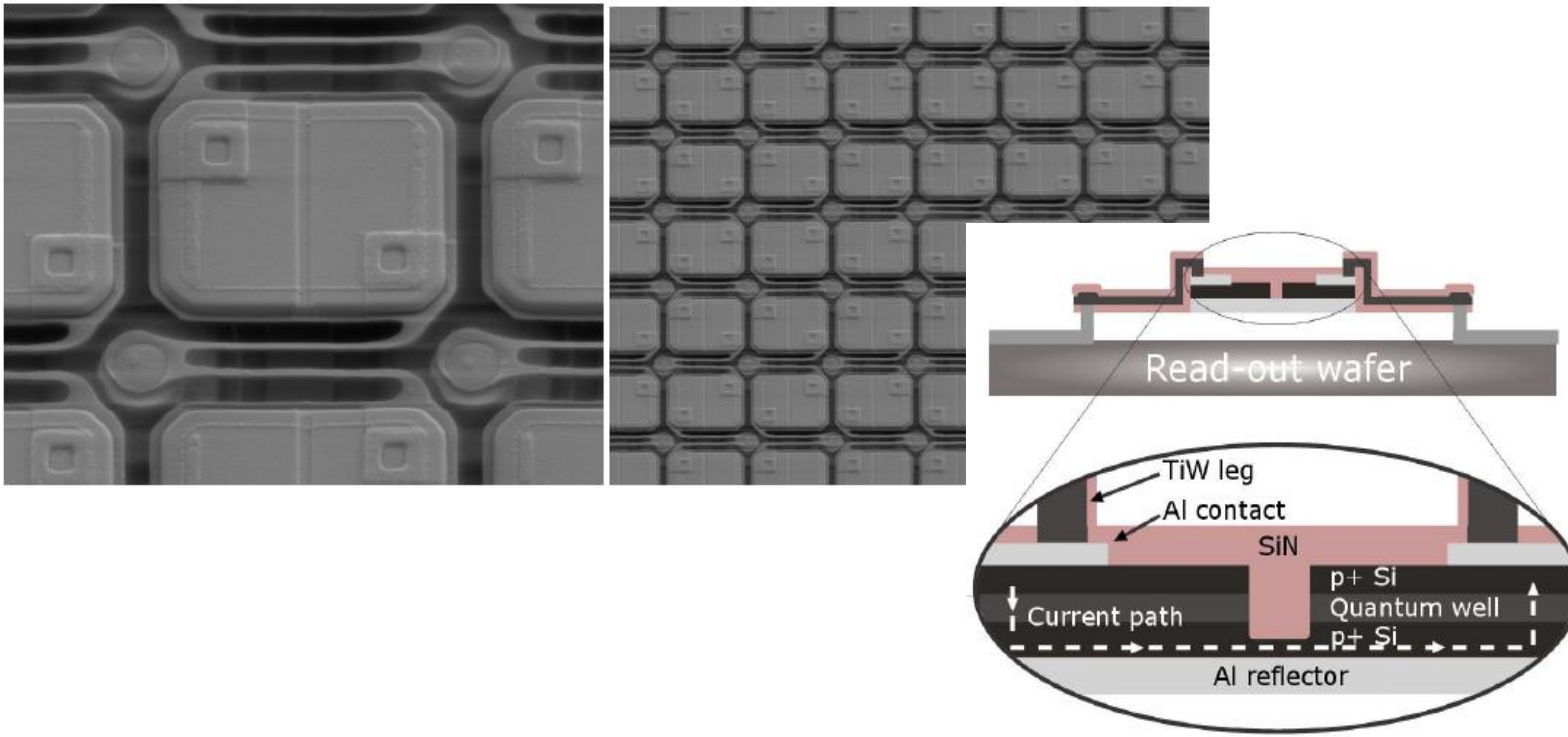
Forsberg, Fredrik, et al. "CMOS-integrated Si/SiGe quantum-well infrared microbolometer focal plane arrays manufactured with very large-scale heterogeneous 3-D integration." *IEEE Journal of Selected Topics in Quantum Electronics* 21.4 (2015): 30-40.

Design of QW Si/SiGe IR Bolometer



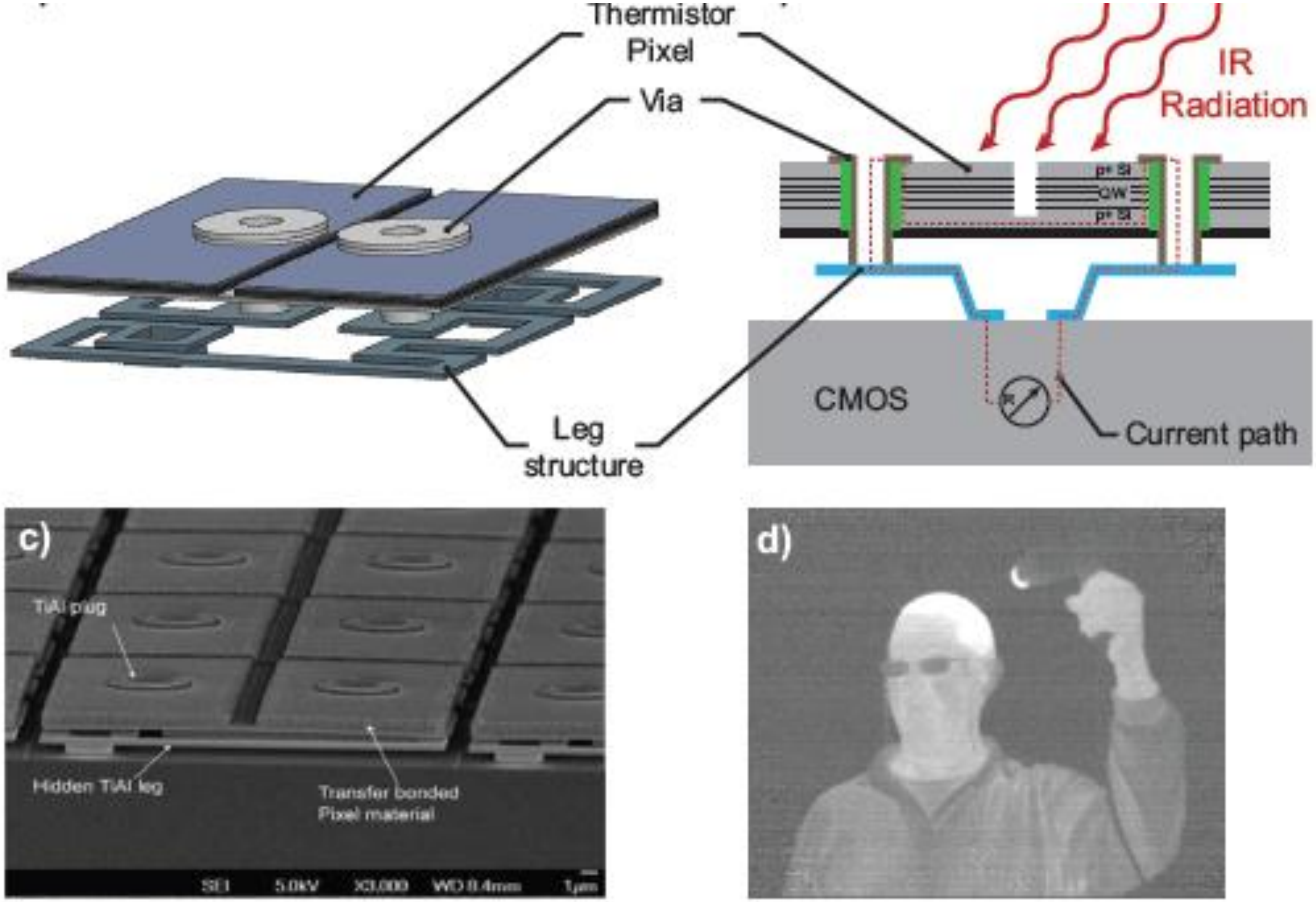
Forsberg, Fredrik, et al. "CMOS-integrated Si/SiGe quantum-well infrared microbolometer focal plane arrays manufactured with very large-scale heterogeneous 3-D integration." *IEEE Journal of Selected Topics in Quantum Electronics* 21.4 (2015): 30-40.

Heterogeneously Integrated 17 µm pitch QW SiGe Bolometers on Fan-Out-Wafers



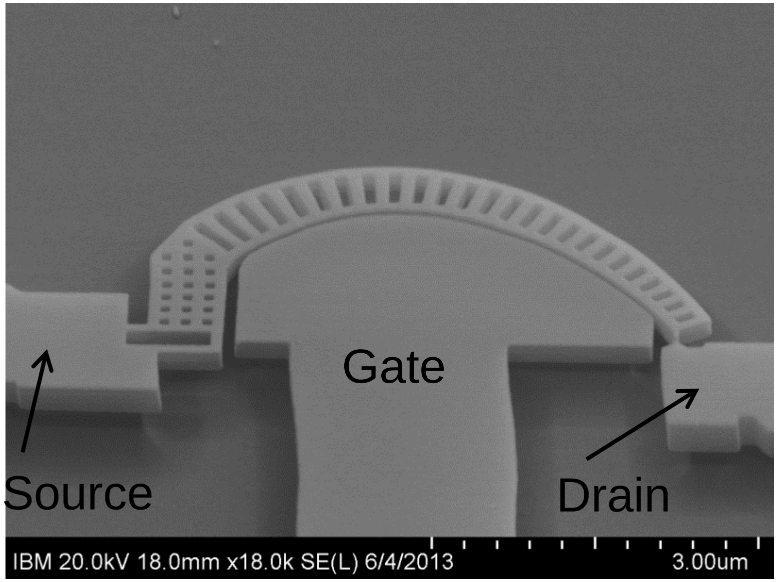
Forsberg, Fredrik, et al. "CMOS-integrated Si/SiGe quantum-well infrared microbolometer focal plane arrays manufactured with very large-scale heterogeneous 3-D integration." *IEEE Journal of Selected Topics in Quantum Electronics* 21.4 (2015): 30-40.

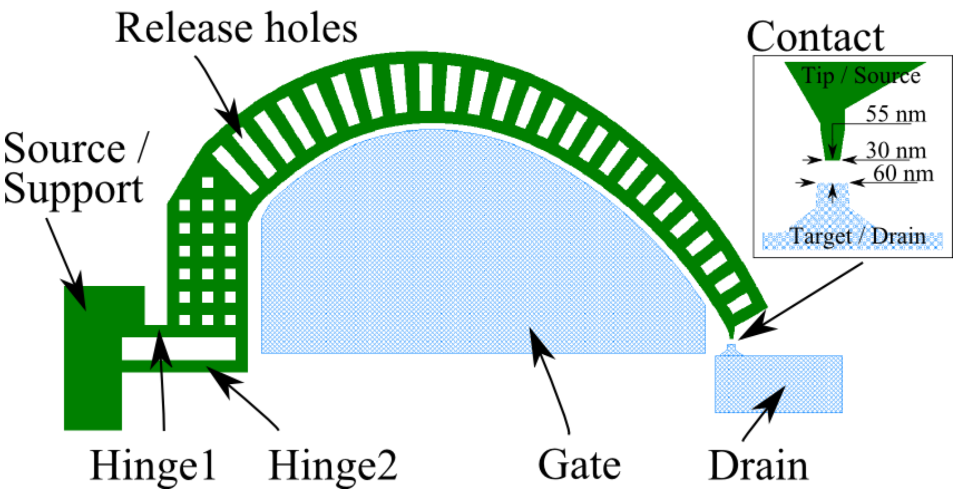
Functional Double-Layer 25 µm pitch IR Bolometers on 0.35 µm CMOS

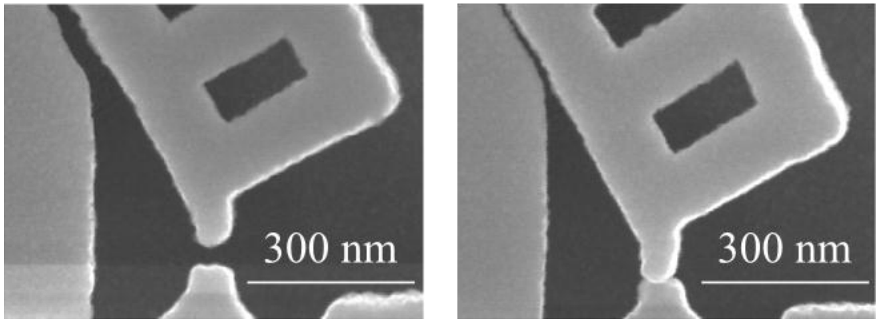


Forsberg, Fredrik, et al. "CMOS-integrated Si/SiGe quantum-well infrared microbolometer focal plane arrays manufactured with very large-scale heterogeneous 3-D integration." *IEEE Journal of Selected Topics in Quantum Electronics* 21.4 (2015): 30-40.

NEMS Switch Design



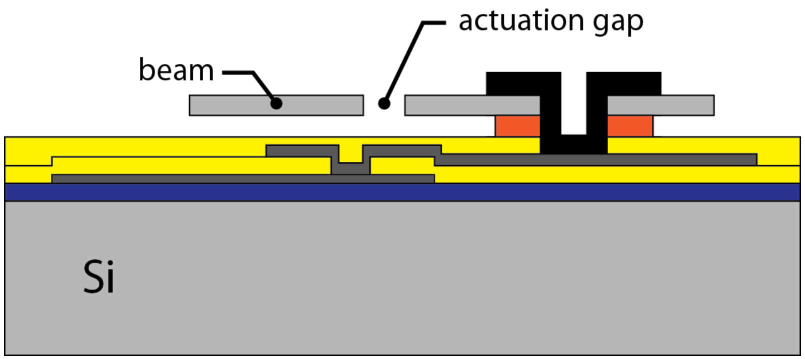




Integration of NEM Switches

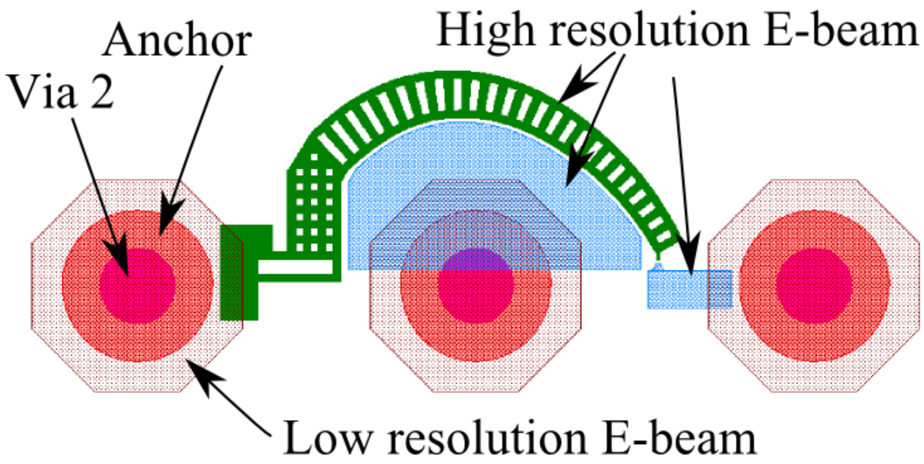
Goal:

NEM switch on top of 2 metal layer interconnect wafer

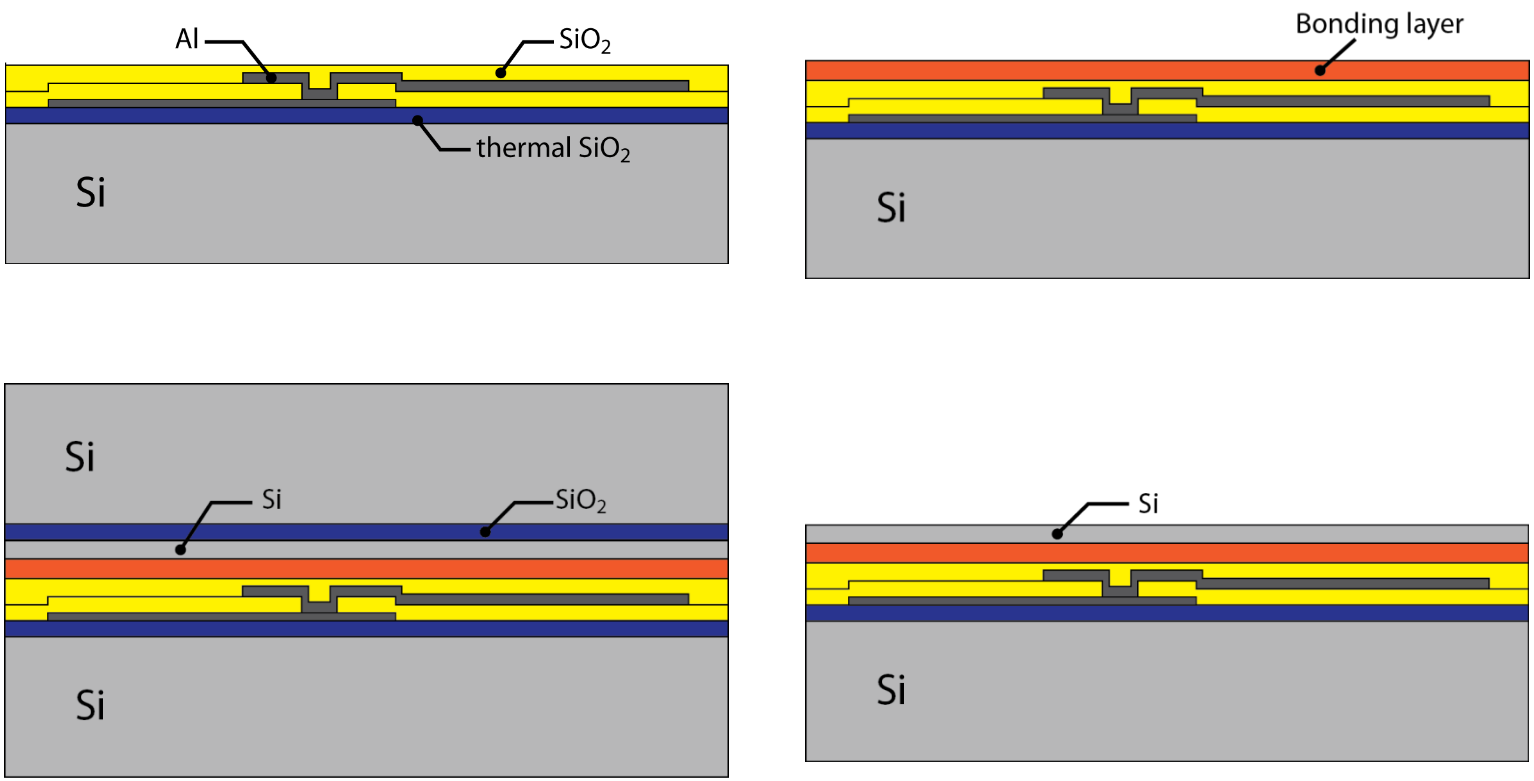


Method:

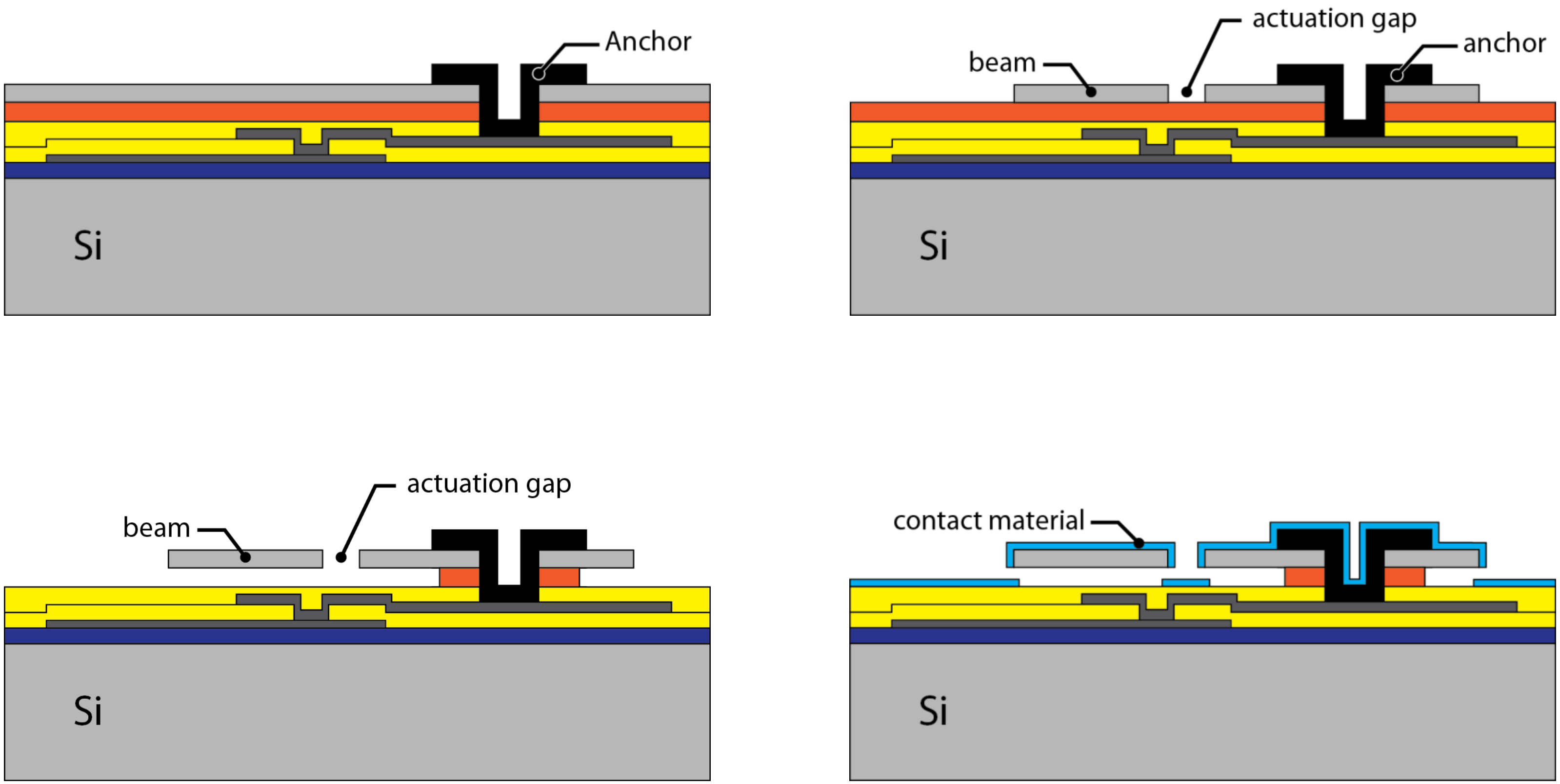
Metal anchors for mechanical stability and electrical connection



Heterogeneous Integration Process



Heterogeneous Integration Process

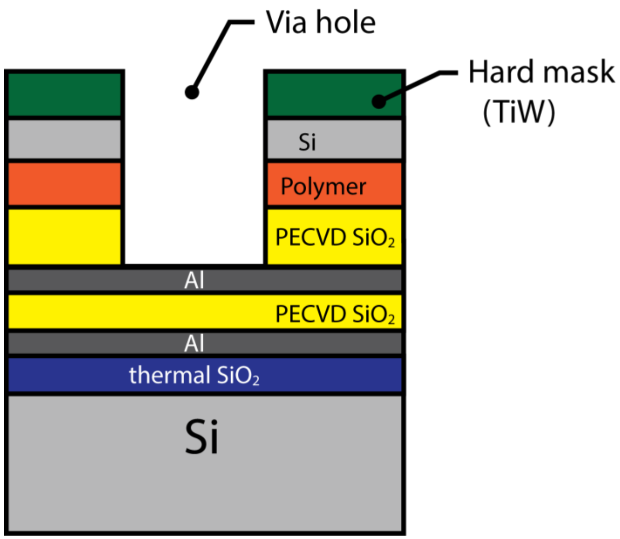


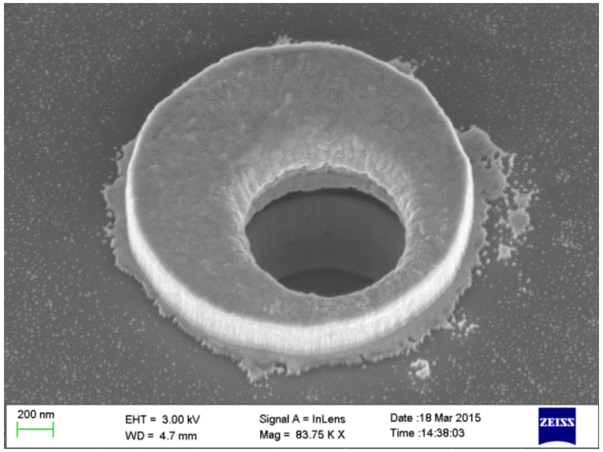
Challenges

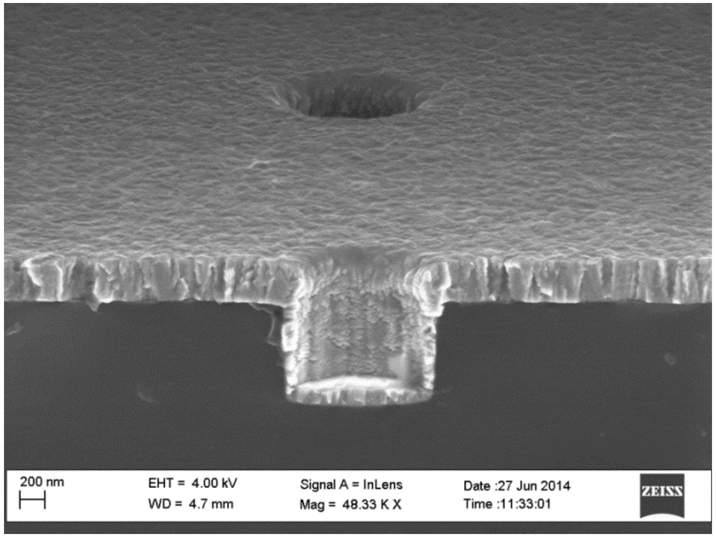
Etching of Anchor holes

- Use hard mask to etch through different materials

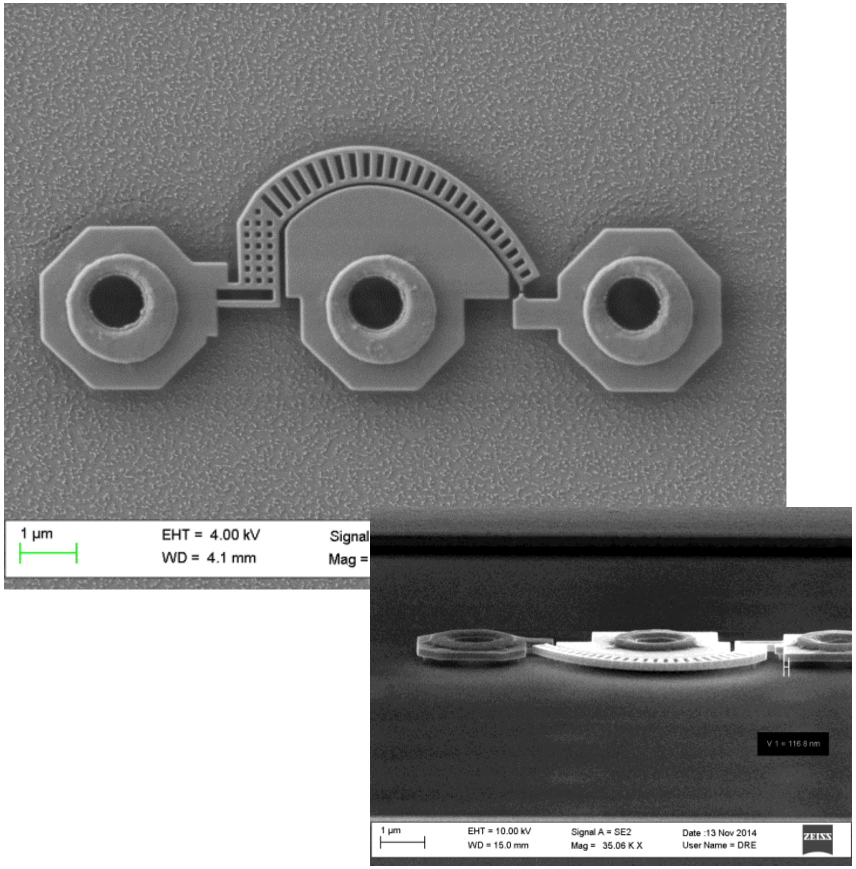
  → How do you know when to stop etching?







Integrated Moni-Si NEM Switches

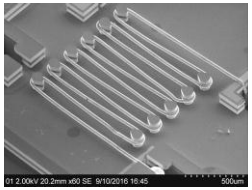


Qin, T., Bleiker, S. J., Rana, S., Niklaus, F., & Pamunuwa, D. (2018). Performance Analysis of Nanoelectromechanical Relay-Based Field-Programmable Gate Arrays. *IEEE Access*.

Research Topics in Group

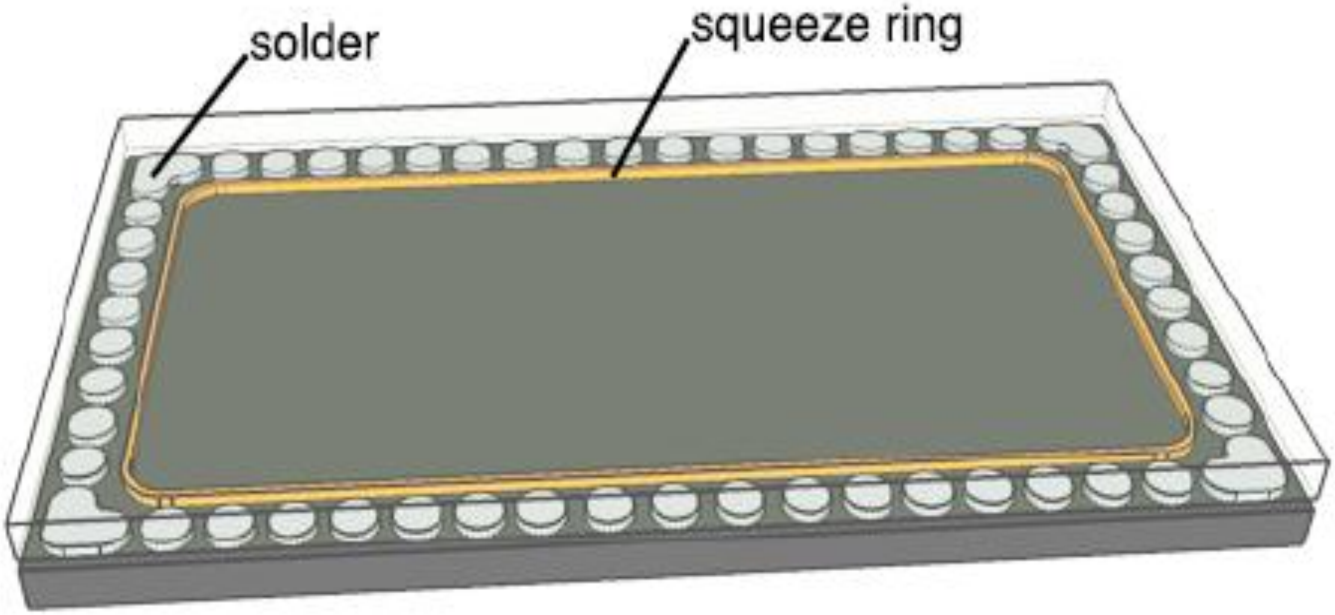
- Heterogeneous 3D Integration for MEMS & NEMS

- **Integration and Packaging for MEMS**



- Nanomanufacturing Technologies and Graphene NEMS

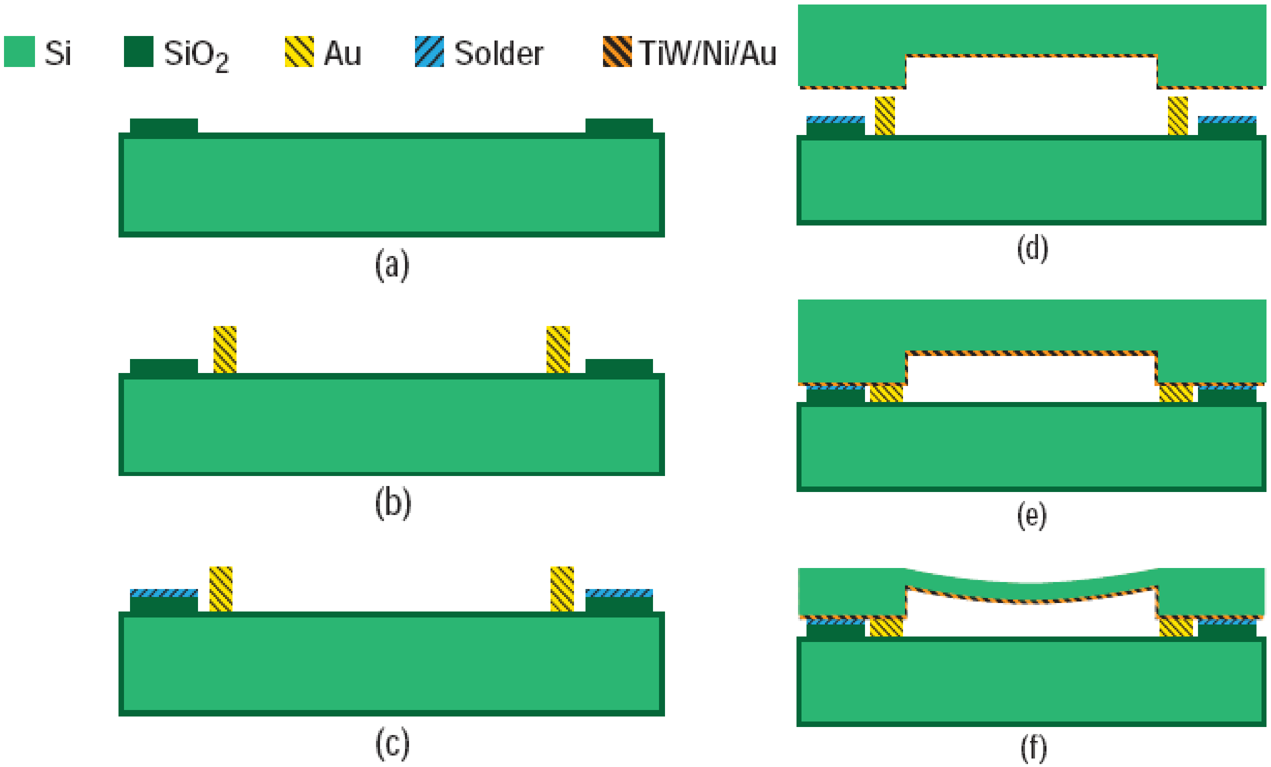
Wafer-Level Vacuum Sealing Using Cold Metal Welding in Combination with Solder Bumps

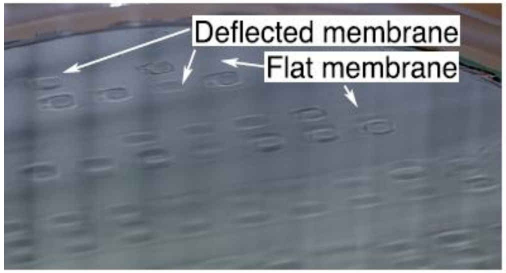


- Au sealing ring prevents solder vaport enter cavity.
- Solder bumps provide bond strength.

Antelius, M., Stemme, G., & Niklaus, F. (2011). Small footprint wafer-level vacuum packaging using compressible gold sealing rings. *Journal of Micromechanics and Microengineering*, *21*(8), 085011.

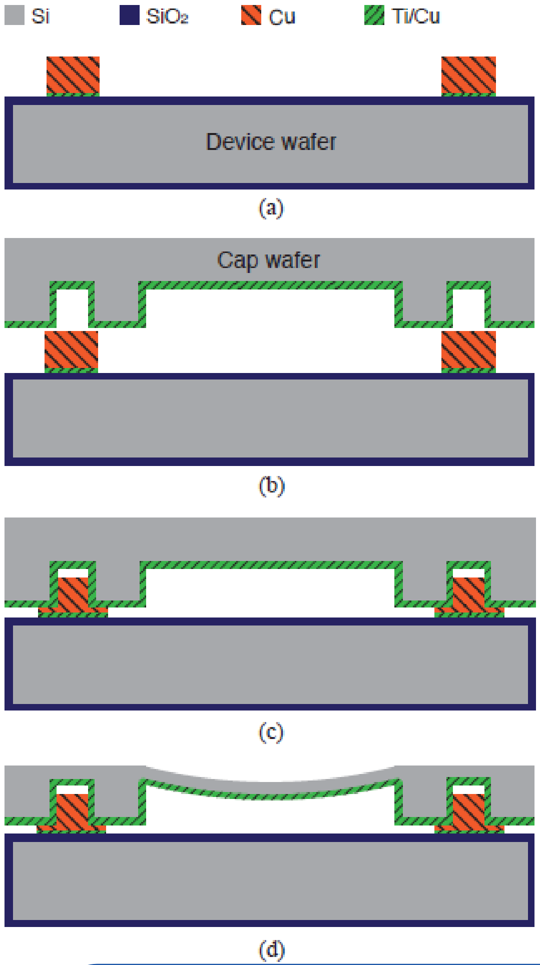
Wafer-Level Vacuum Sealing: Process Flow

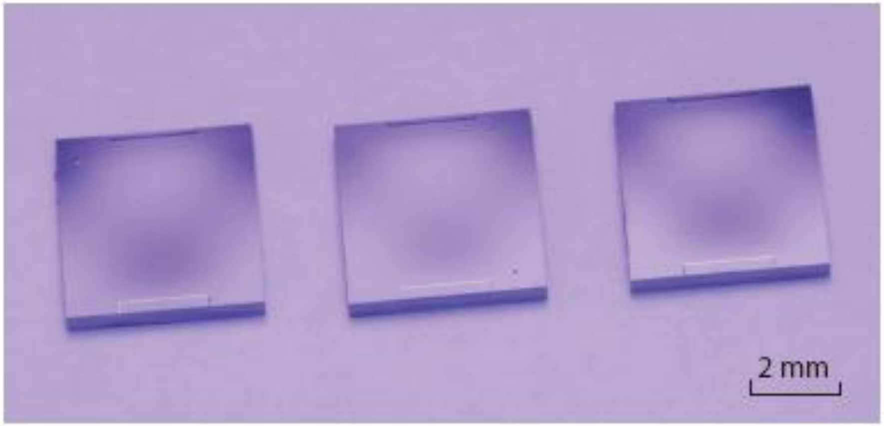


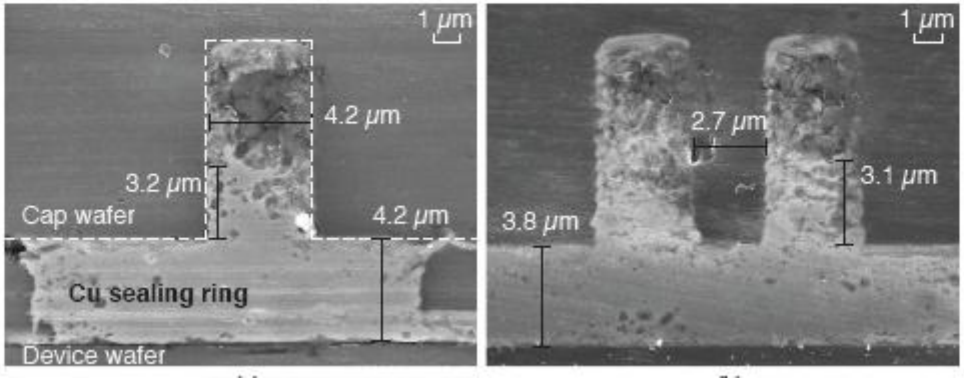


Antelius, M., Stemme, G., & Niklaus, F. (2011). Small footprint wafer-level vacuum packaging using compressible gold sealing rings. *Journal of Micromechanics and Microengineering*, *21*(8), 085011.

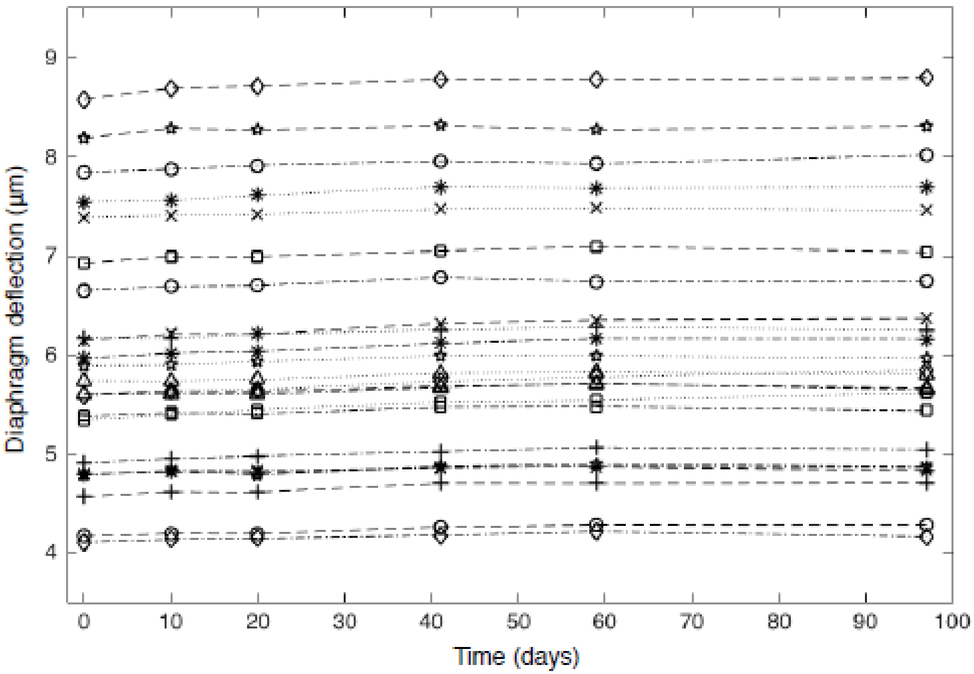
Wafer-Level Low-Temperature Vacuum Sealing Using 8 μm Wide Copper Rings







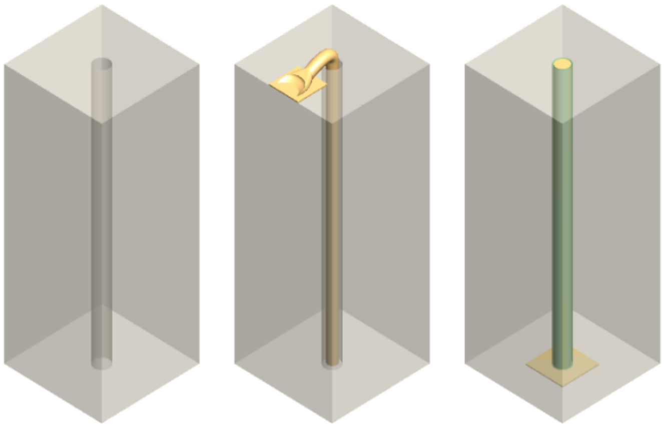
Wafer-Level Low-Temperature Vacuum Sealing Using Copper Sealing



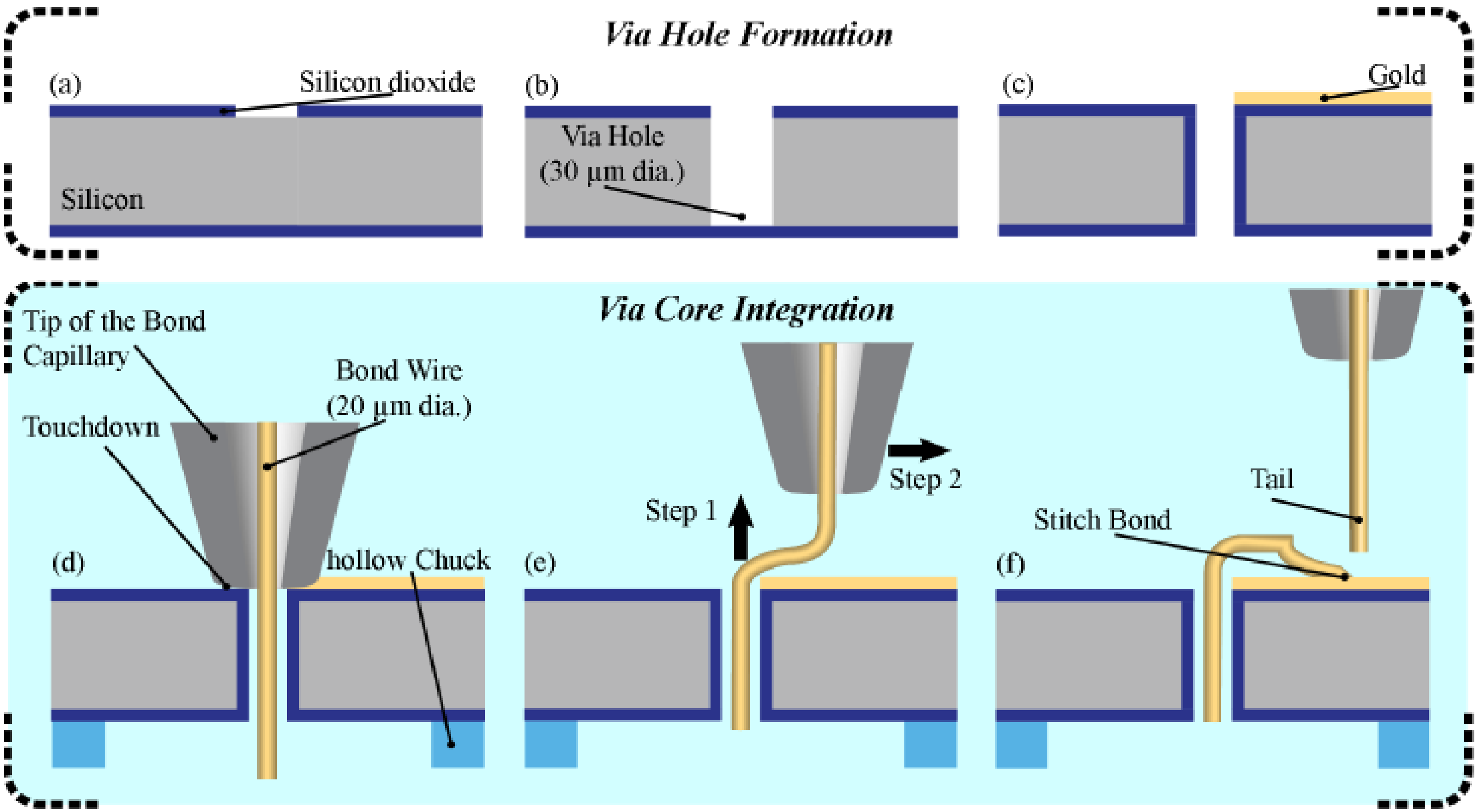
Gas	O2G2 design		O2G3 design	
	Pressure (mbar)	Percent (%)	Pressure (mbar)	Percent (%)
H_2	2.9×10^{-2}	63.07	0	0
CO_2	1.1×10^{-2}	23.92	0	0
CO	5.1×10^{-3}	11.09	0	0
CH_4	0	0	2.5×10^{-2}	97.66
CHs[a]	6.7×10^{-4}	1.46	4.5×10^{-4}	1.76
Ar	2.1×10^{-4}	0.46	1.3×10^{-4}	0.51
He	0	0	1.8×10^{-5}	0.07
O_2	0	0	0	0
N_2	0	0	0	0
H_2O	0	0	0	0
Total	4.6×10^{-2}	100.00	2.6×10^{-2}	100.00

Wire Bonded TSVs

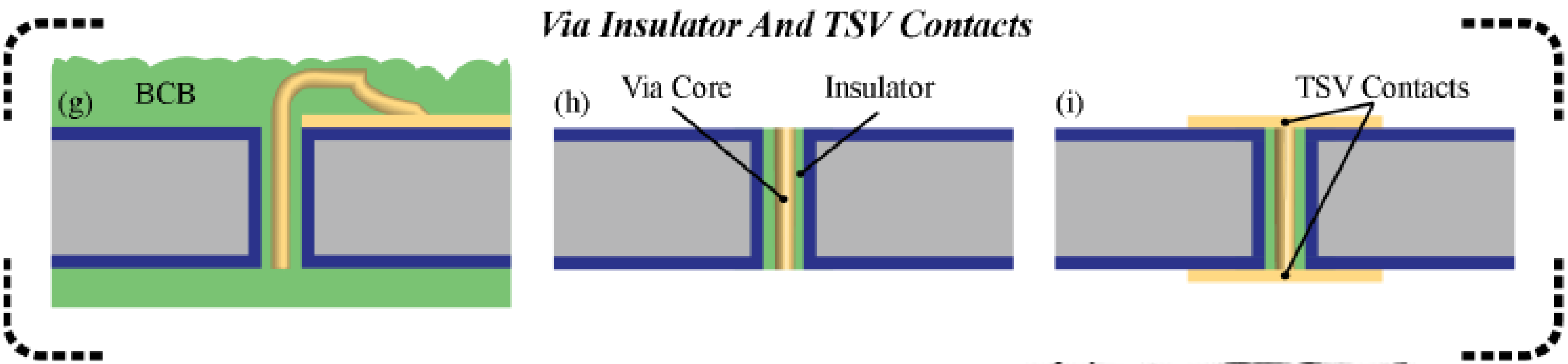
- Low-cost for low to medium TSV density
- Enable high aspect ratio TSV formation
- No lithography (mask-less) TSV formation
- Low temperature budget approach

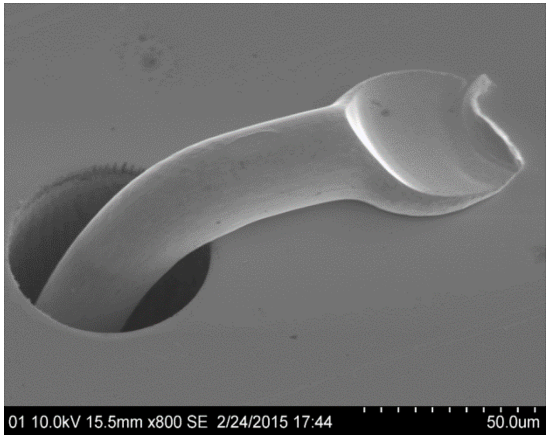


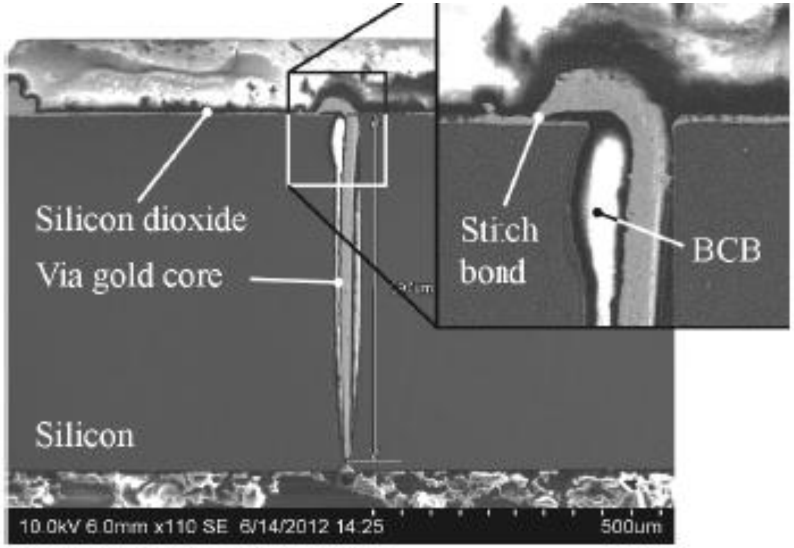
TSVs Manufacturing Using Wire Bonding



Gold TSVs with Aspect Ratios > 20







Schröder, Stephan, et al. "Very high aspect ratio through silicon vias (TSVs) using wire bonding." *Solid-State Sensors, Actuators and Microsystems (TRANSDUCERS & EUROSENSORS XXVII), 2013 Transducers & Eurosensors XXVII: The 17th International Conference on*. IEEE, 2013.

Sealing of Liquids in MEMS Cavities Using Cold Metal Plugging

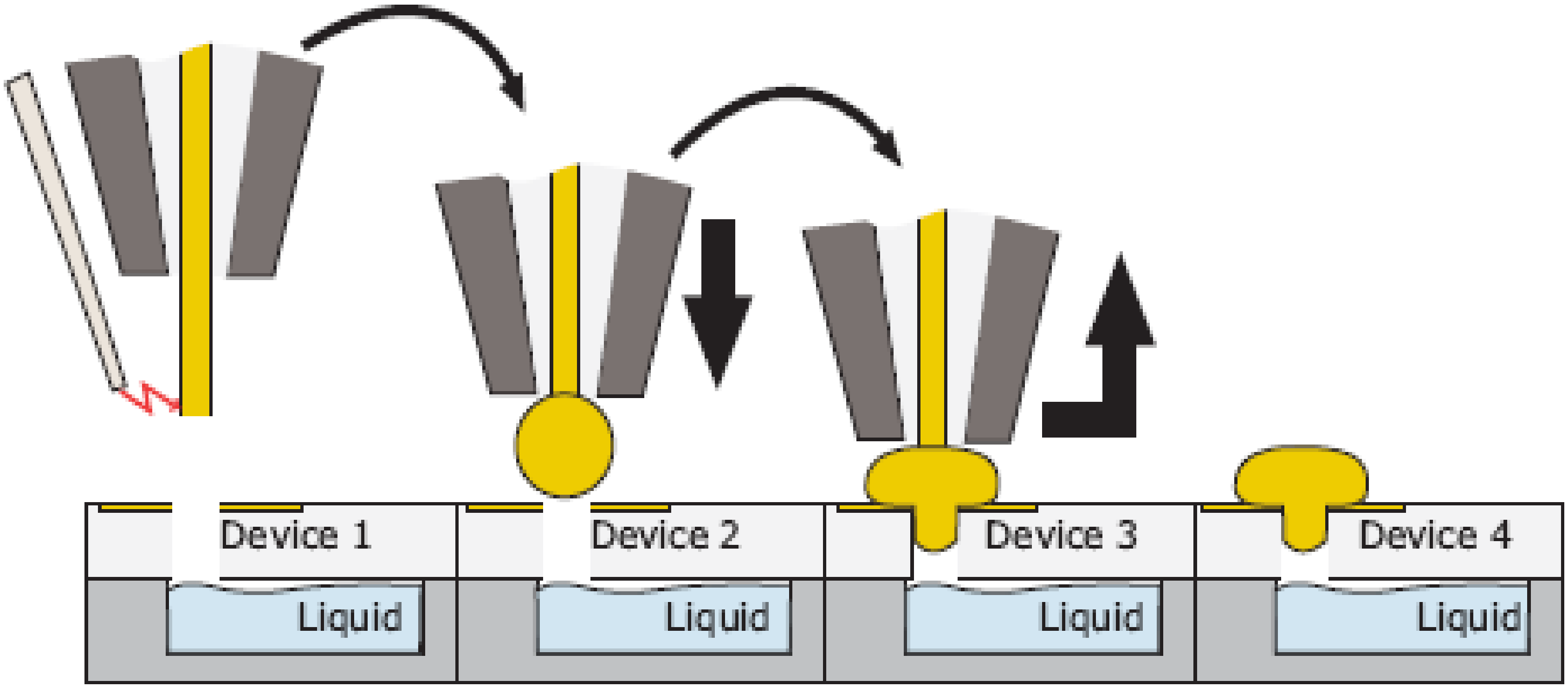
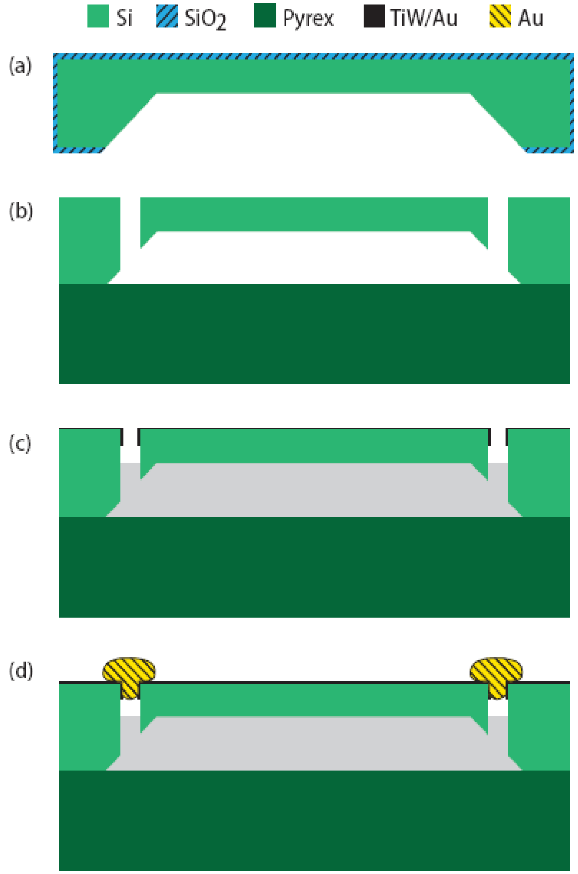
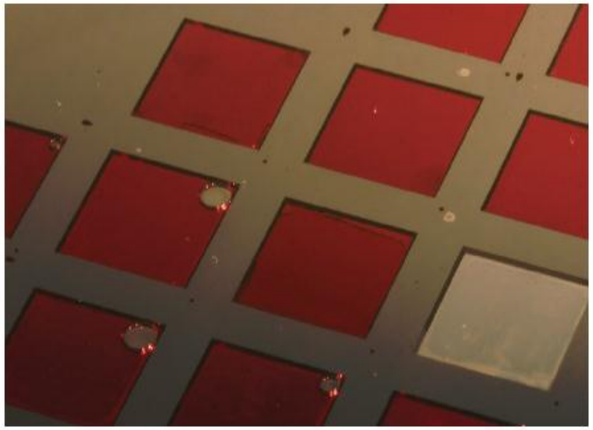
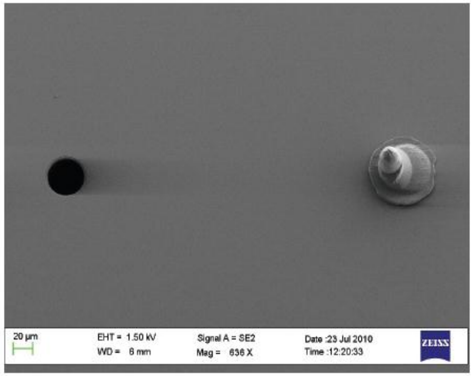


Image source: Antelius, Proc Transducers 2011, KTH

Sealing of Liquids in MEMS Cavities Using Cold Metal Plugging







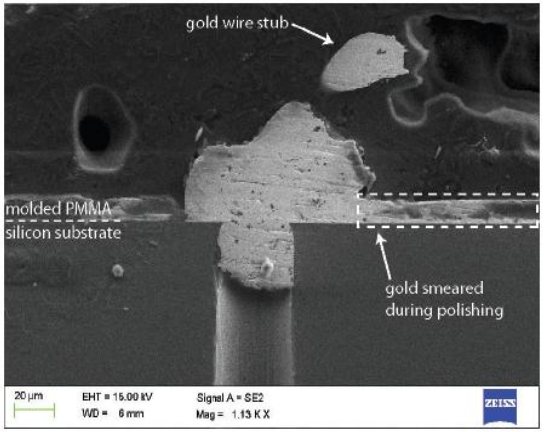


Image source: Antelius, Proc Transducers 2011, KTH

Wafer-Level Vacuum Sealing Using Cold Metal Plugging

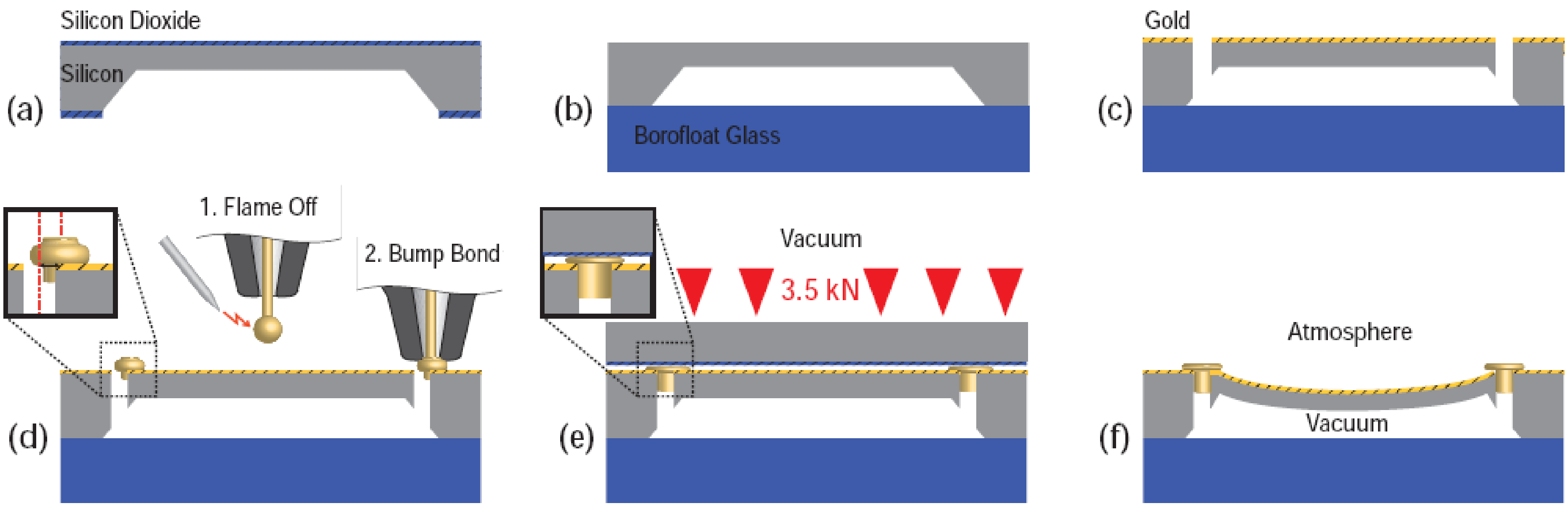
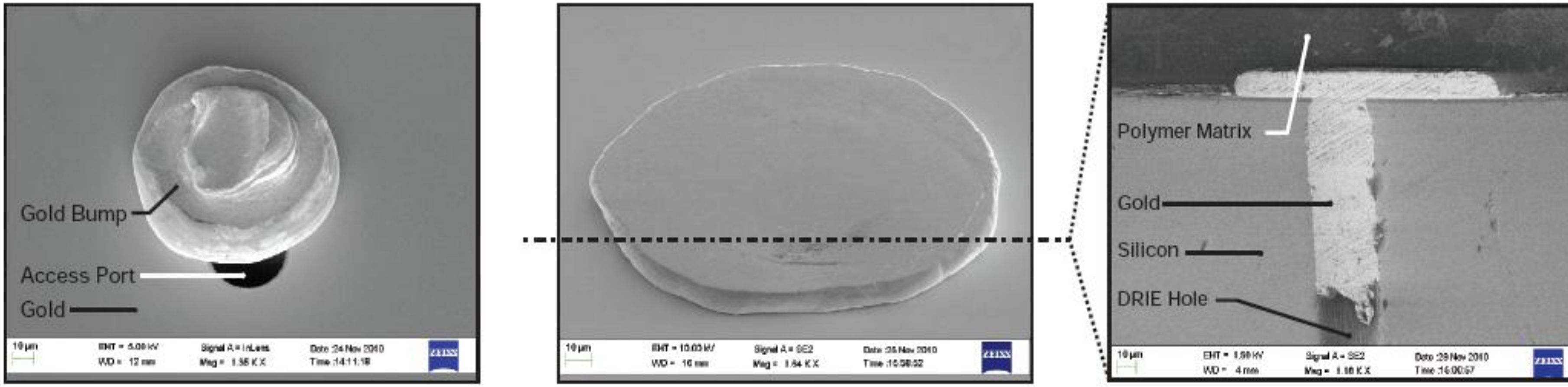
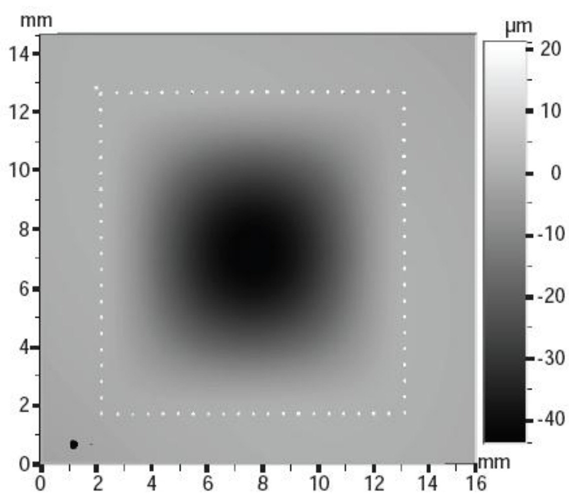


Image source: Antelius, Proc Transducers 2011, KTH

Wafer-Level Vacuum Sealing Using Cold Metal Plugging



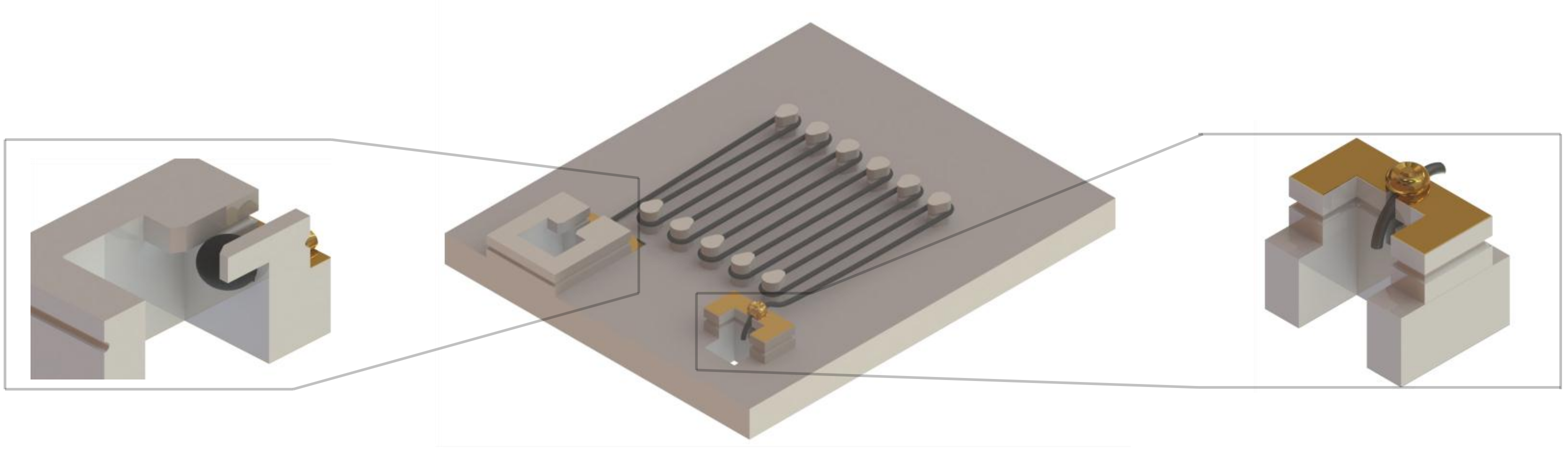


Gas	Pressure, 2 ports		Pressure, 80 ports	
	[mbar]	%	[mbar]	%
H_2O	3.33×10^{-3}	56.96[a]	0	0
Ar	1.00×10^{-3}	17.17	6.15×10^{-4}	75.11
N_2	8.52×10^{-4}	14.56	0	0
H_2	5.25×10^{-4}	8.97	0	0
CH_4	8.75×10^{-5}	1.50	0	0
O_2	2.77×10^{-5}	0.47	0	0
CO_2	2.18×10^{-5}	0.37	2.04×10^{-4}	24.86
He	0	0	1.89×10^{-7}	0.02
Ne	0	0	0	0
C_2H_6	0	0	0	0
C_3H_8	0	0	0	0
CO	0	0	0	0
Kr	0	0	0	0
Total	5.85×10^{-3}	100.00	8.19×10^{-4}	100.00

Image source: Antelius, Proc Transducers 2011, KTH

Wire Bonded Infrared Emitter

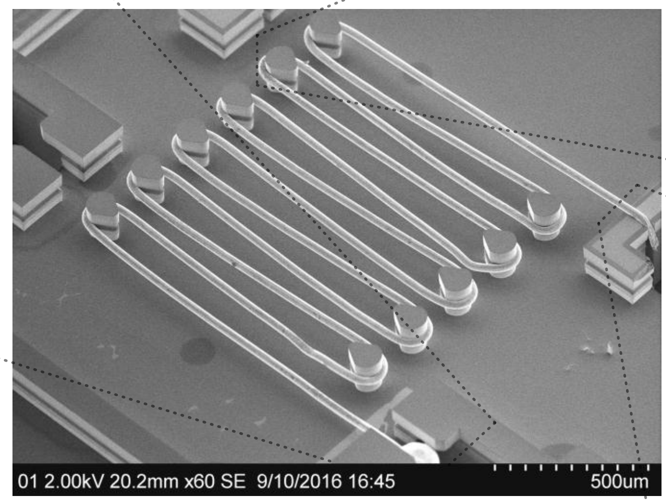
- Joule-heated suspended Kanthal filament
- Integration using an automated wire bonding tool
- Mechanical fixation and placement by
  - Attachment structures for free air ball & wire
  - Guiding posts



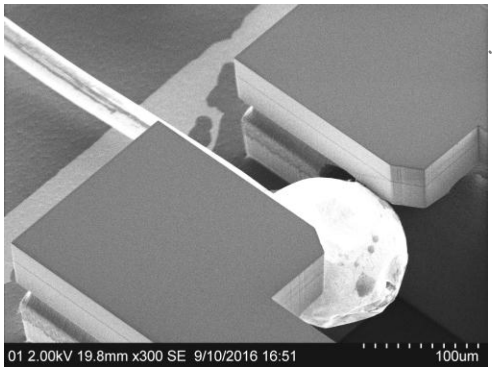
Schröder, Stephan, et al. "Fabrication of an infrared emitter using a generic integration platform based on wire bonding." *Journal of Micromechanics and Microengineering* 26.11 (2016): 115010.

Filament Integration Results

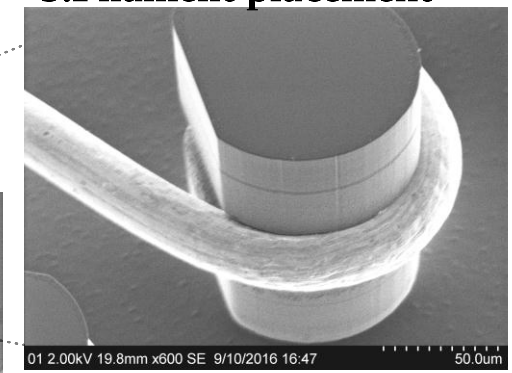
1.Filament Emitter



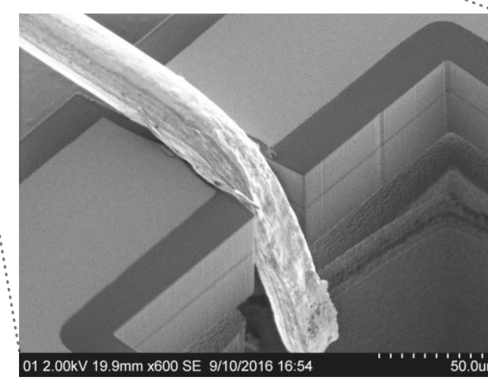
2.Free air ball attachment



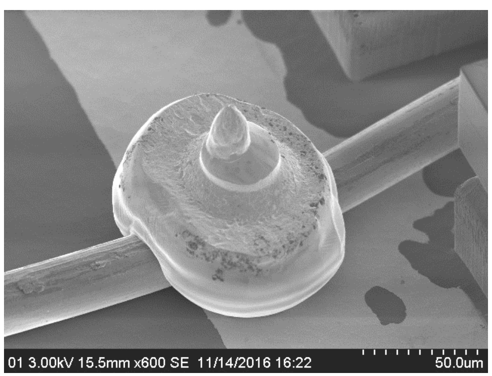
3.Filament placement



4.Filament attachment



5.Electrical contact



Fabrication of High-Aspect Ratio TSVs by Magnetic Assembly of Metal Studs

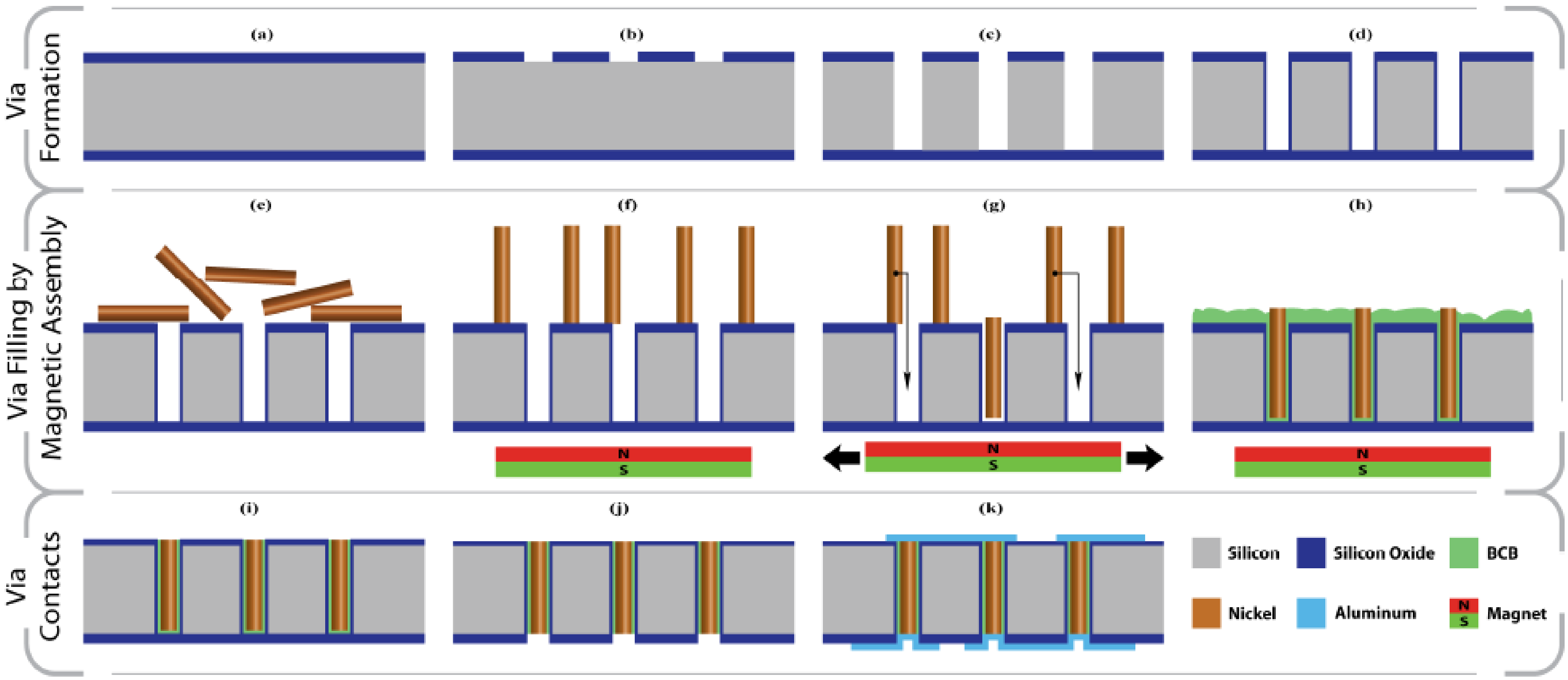
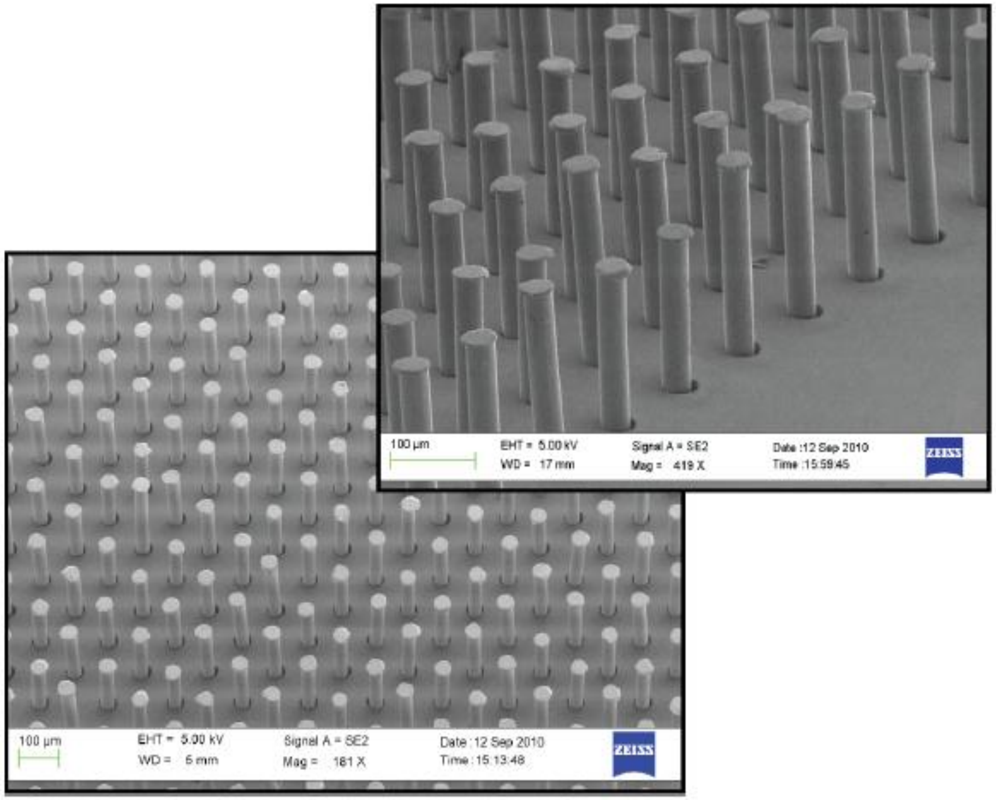


Image source: Fischer, Proc MEMS 2011, KTH

High-Aspect Ratio Nickel TSVs



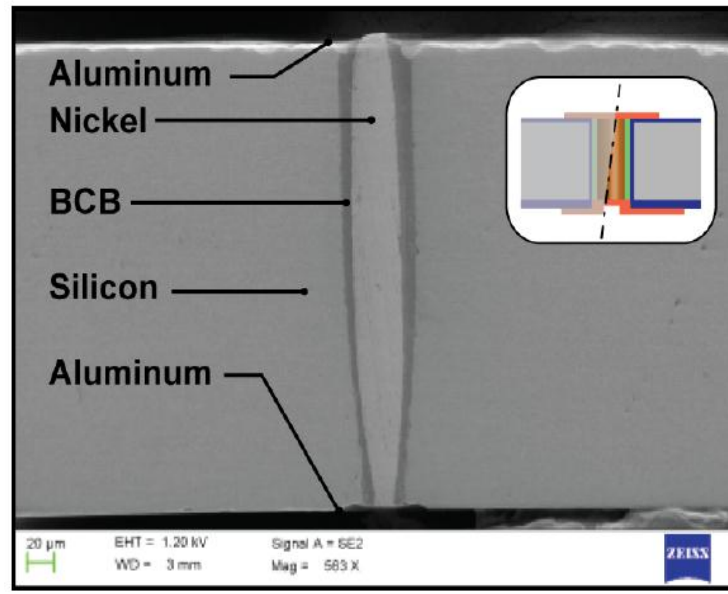
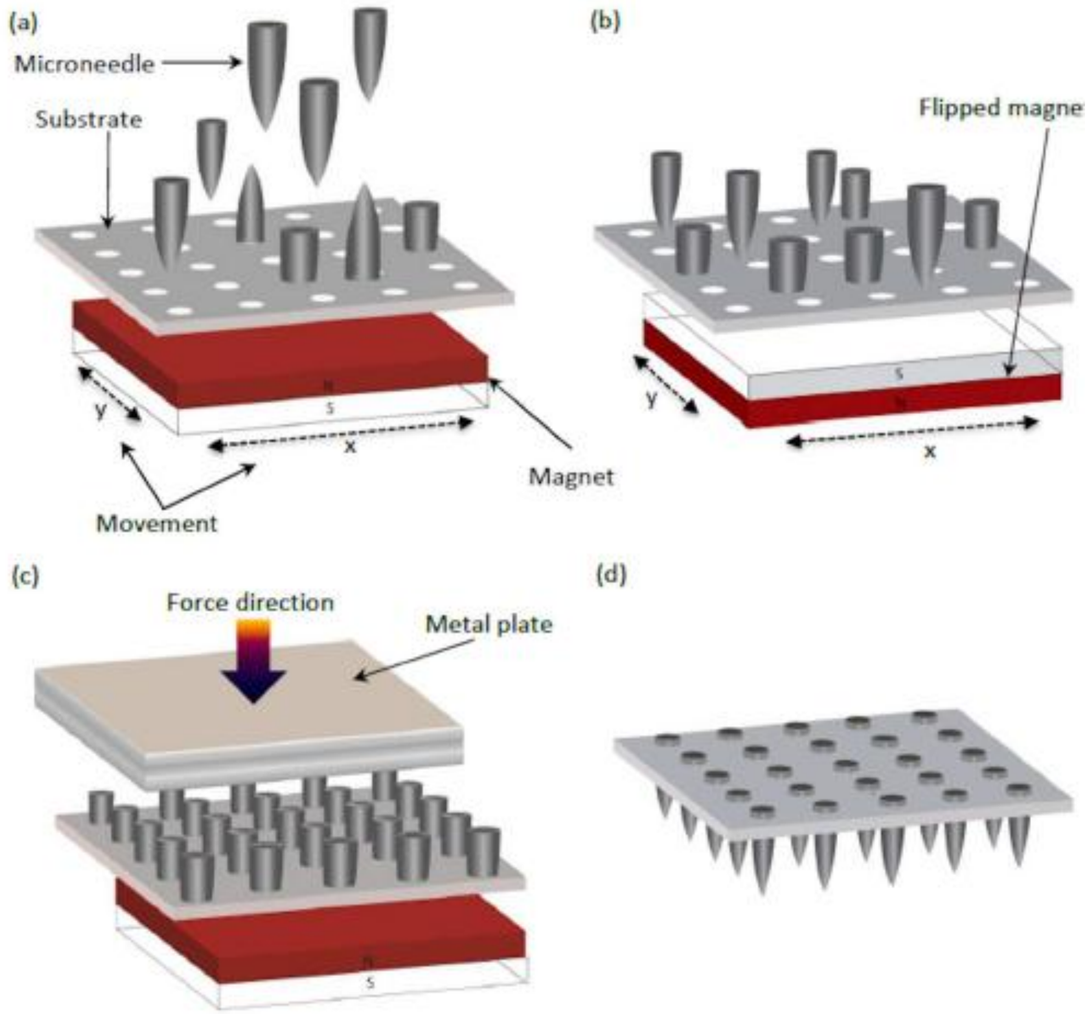


Image source: Fischer, Proc MEMS 2011, KTH

Robotic Magnetic Self-assembly of TSVs

Image source: Fischer, Proc MEMS 2011, KTH

Magnetic Self-assembly for Stretchable Microneedle Patches

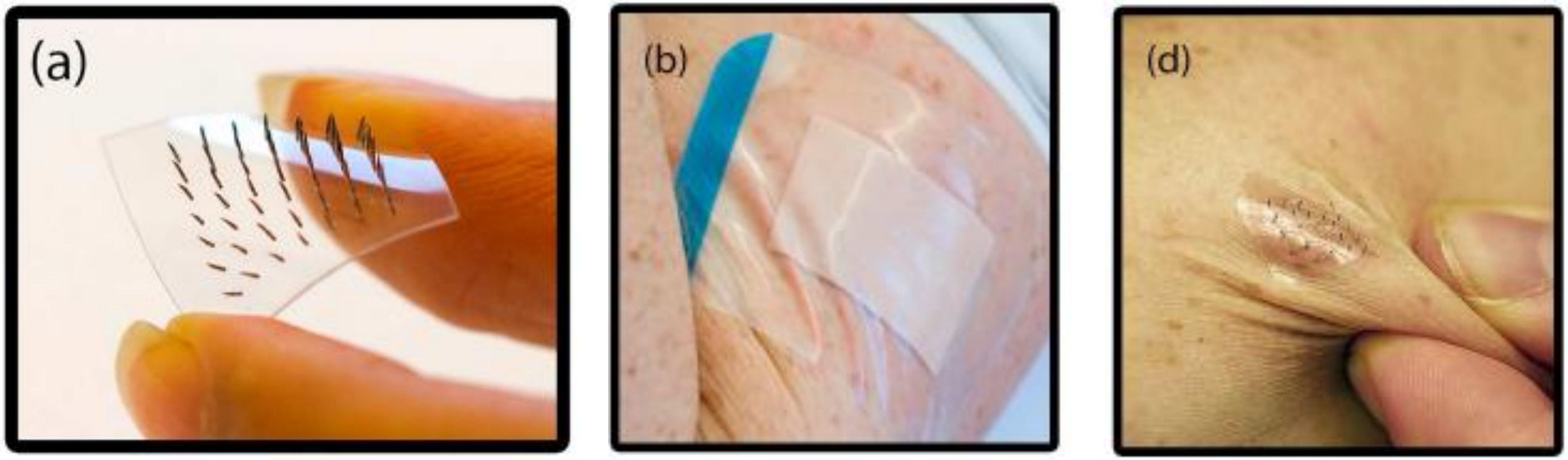


Rajabi, M., Roxhed, N., Shafagh, R. Z., Haraldson, T., Fischer, A. C., van der Wijngaart, W., ... & Niklaus, F. (2016). Flexible and stretchable microneedle patches with integrated rigid stainless steel microneedles for transdermal biointerfacing. *PloS one*, *11*(12), e0166330.

Magnetic Self-assembly for Stretchable Microneedle Patches

Combination of :

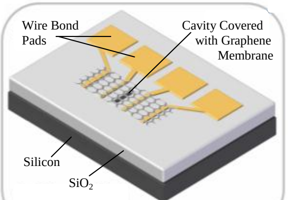
Stretchable and flexible substrate for comfort; and
Sharp and stiff needles for reliable penetration



Rajabi, M., Roxhed, N., Shafagh, R. Z., Haraldson, T., Fischer, A. C., van der Wijngaart, W., ... & Niklaus, F. (2016). Flexible and stretchable microneedle patches with integrated rigid stainless steel microneedles for transdermal biointerfacing. *PloS one*, *11*(12), e0166330.

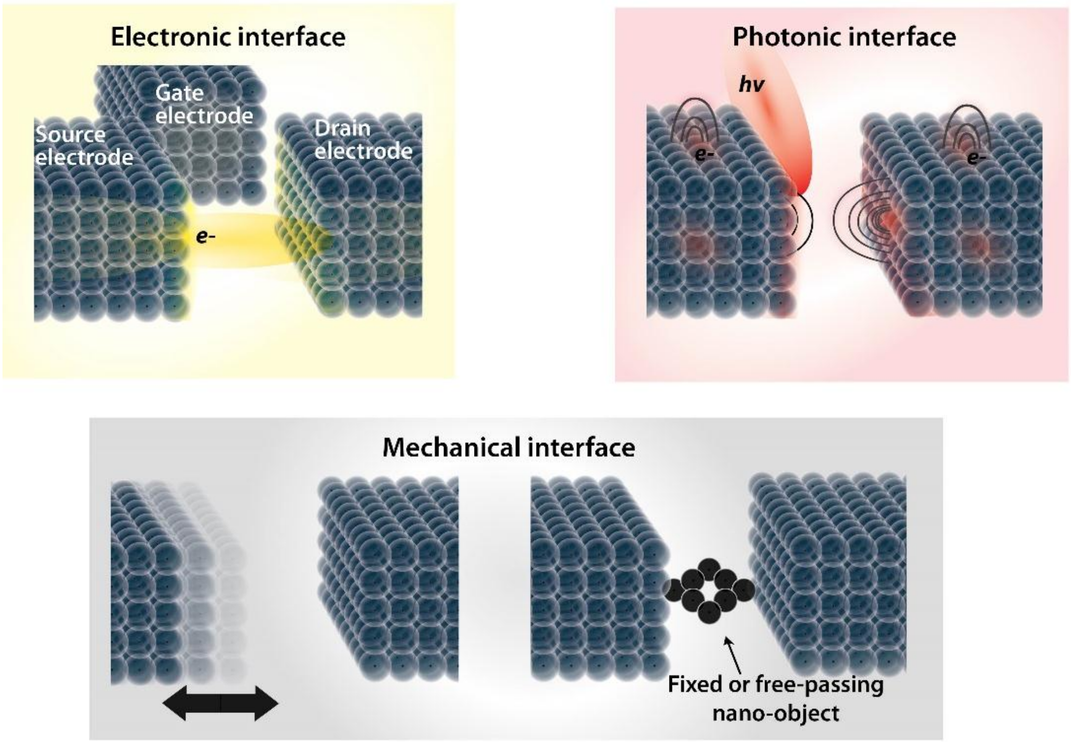
Research Topics in Group

- Heterogeneous 3D Integration for MEMS & NEMS
- Integration and Packaging for MEMS
- **Nanomanufacturing Technologies and Graphene NEMS**



Schematic of Pressure Sensor

Nanogap Electrodes

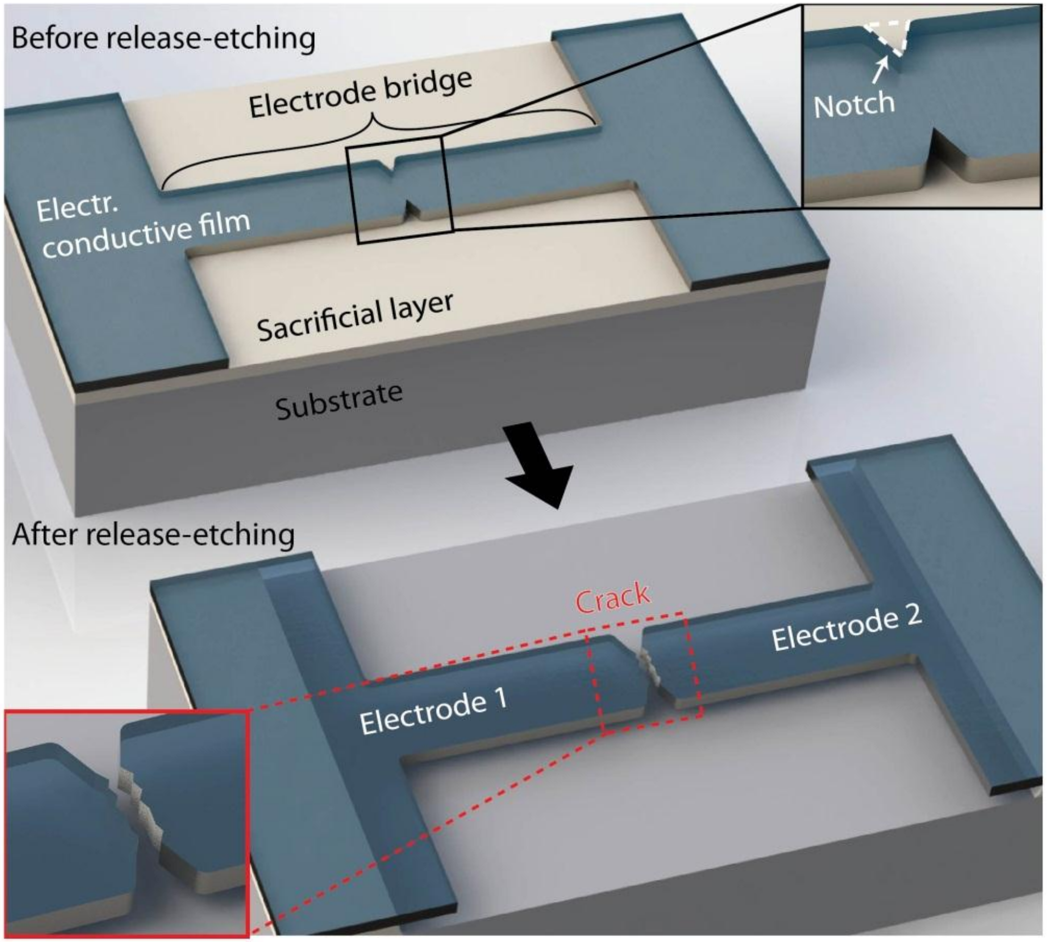


Nanogap electronics:

Require sub-3 nm wide gaps between electrodes !

Major problem: Extremely difficult to realize

Scalable Fabrication of Crack-Defined Nanogap Electrodes

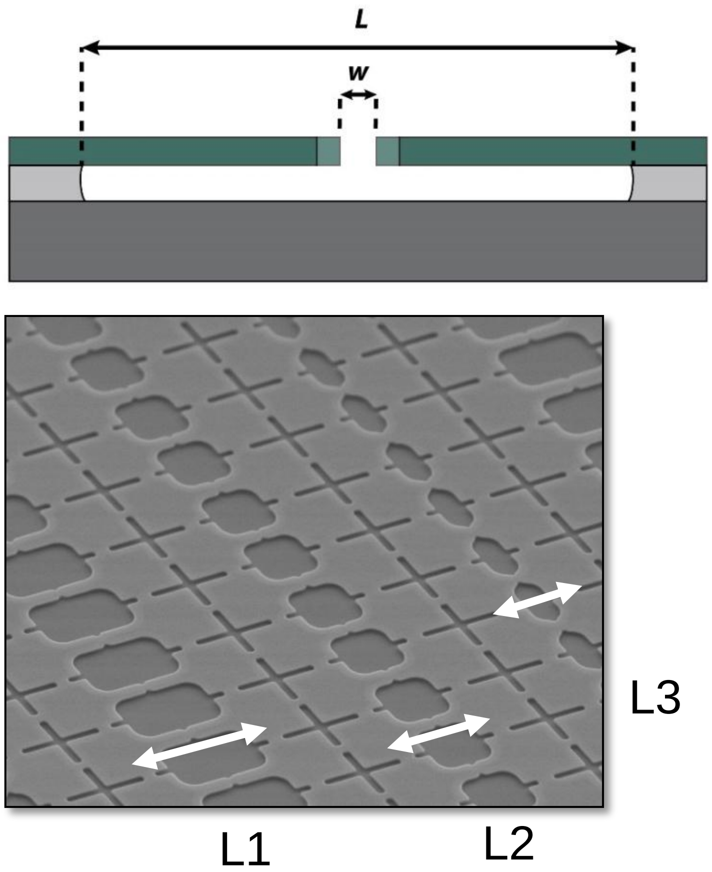


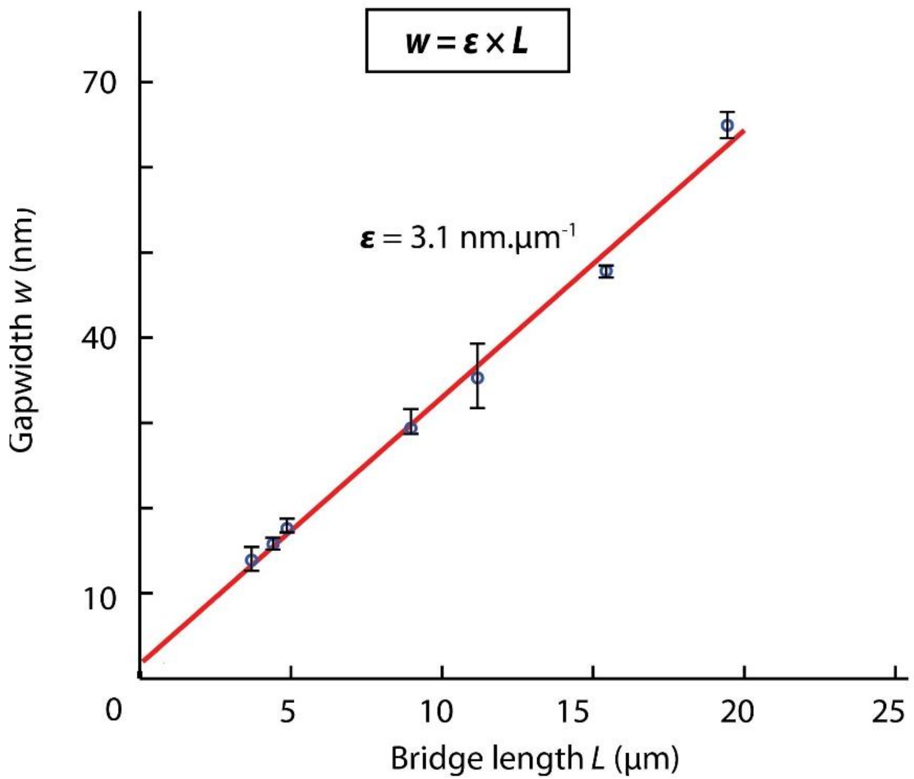
- Control of gap size: 1-100 nm
- Realization of tunneling junctions
- Massively parallel fabrication

Valentin Dubois, Frank Niklaus, and Göran Stemme. "Crack-Defined Electronic Nanogaps." *Adv. Mater.* (2016).

Control of Gap Size

1 µm in electrode bridge length ⬌ **3.1 nm** in nanogap width

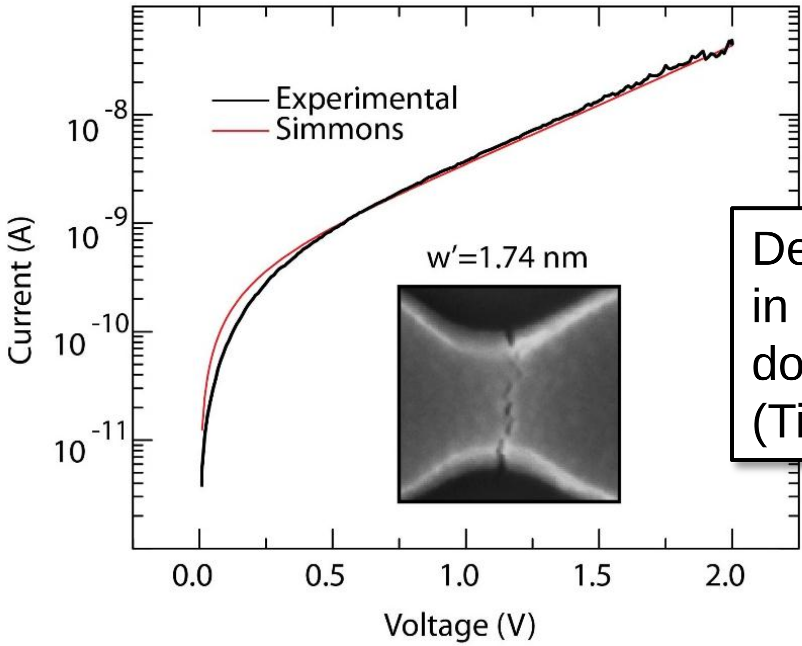




Valentin Dubois, Frank Niklaus, and Göran Stemme. "Crack-Defined Electronic Nanogaps." *Adv. Mater.* (2016).

Nanogap Tunneling Junctions

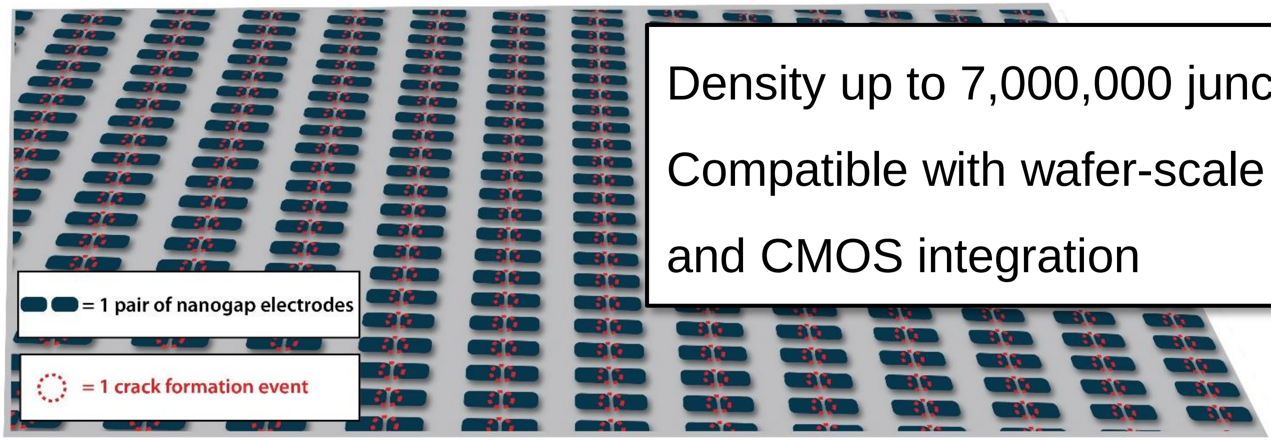
Electron quantum tunneling occurs with **sub-3 nm nanogaps**



Demonstration of quantum tunneling in crack-defined nanogap electrodes down to **sub-1 nm** in titanium nitride (TiN) and gold (Au)

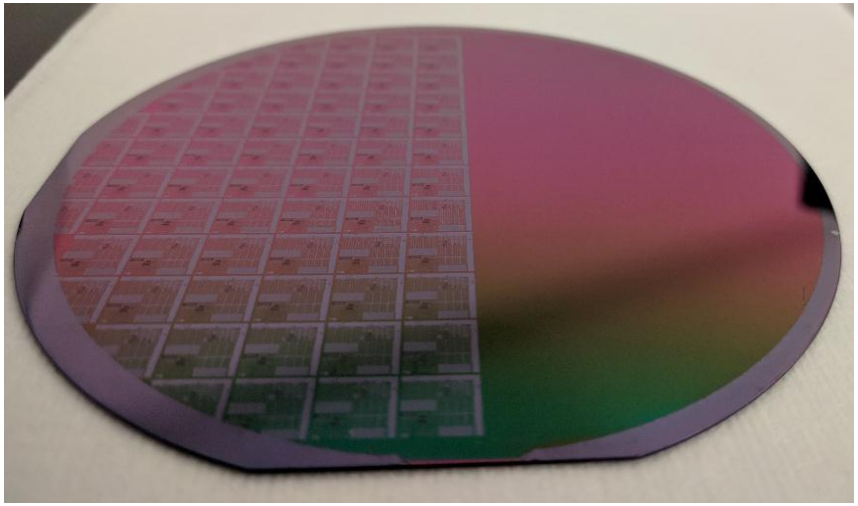
Valentin Dubois, Frank Niklaus, and Göran Stemme. "Crack-Defined Electronic Nanogaps." *Adv. Mater.* (2016).

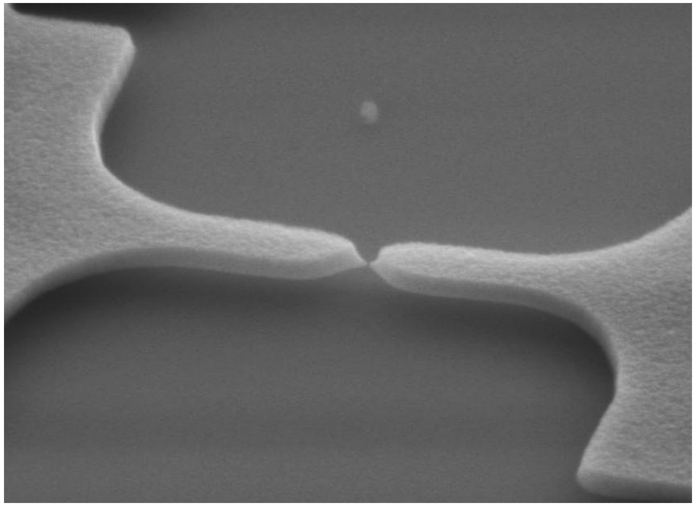
Massively Parallel Fabrication



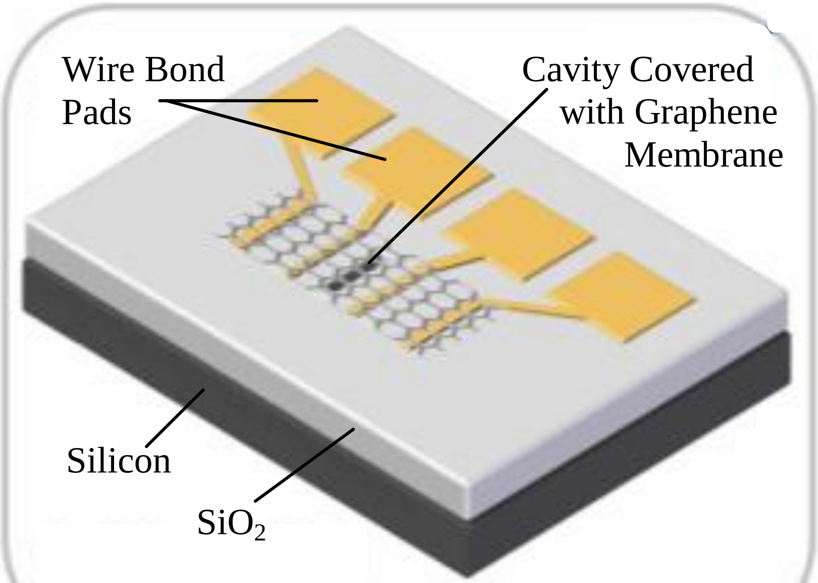
Density up to 7,000,000 junctions per cm^2

Compatible with wafer-scale processes and CMOS integration

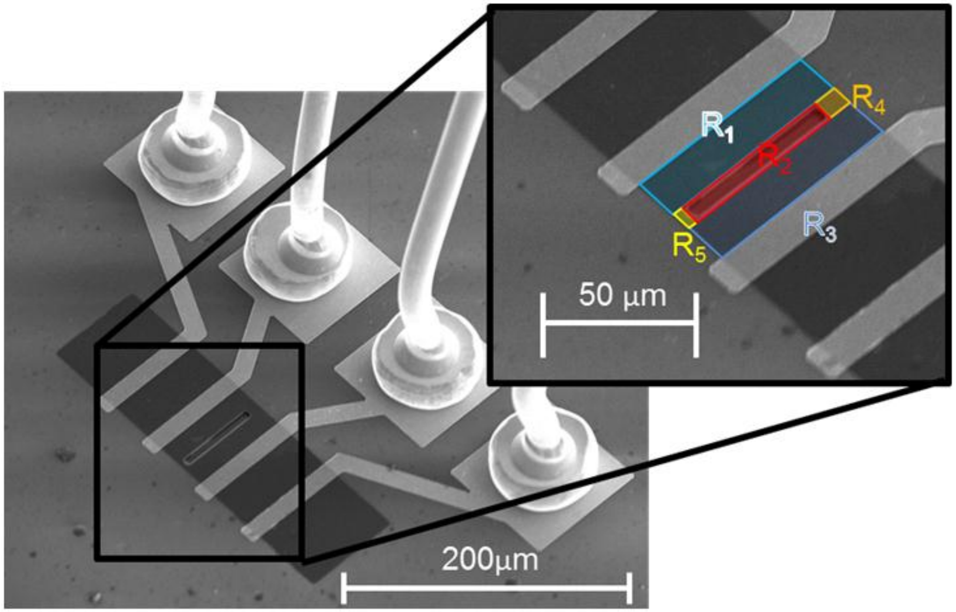




Graphene-Based NEMS: Pressure Sensing

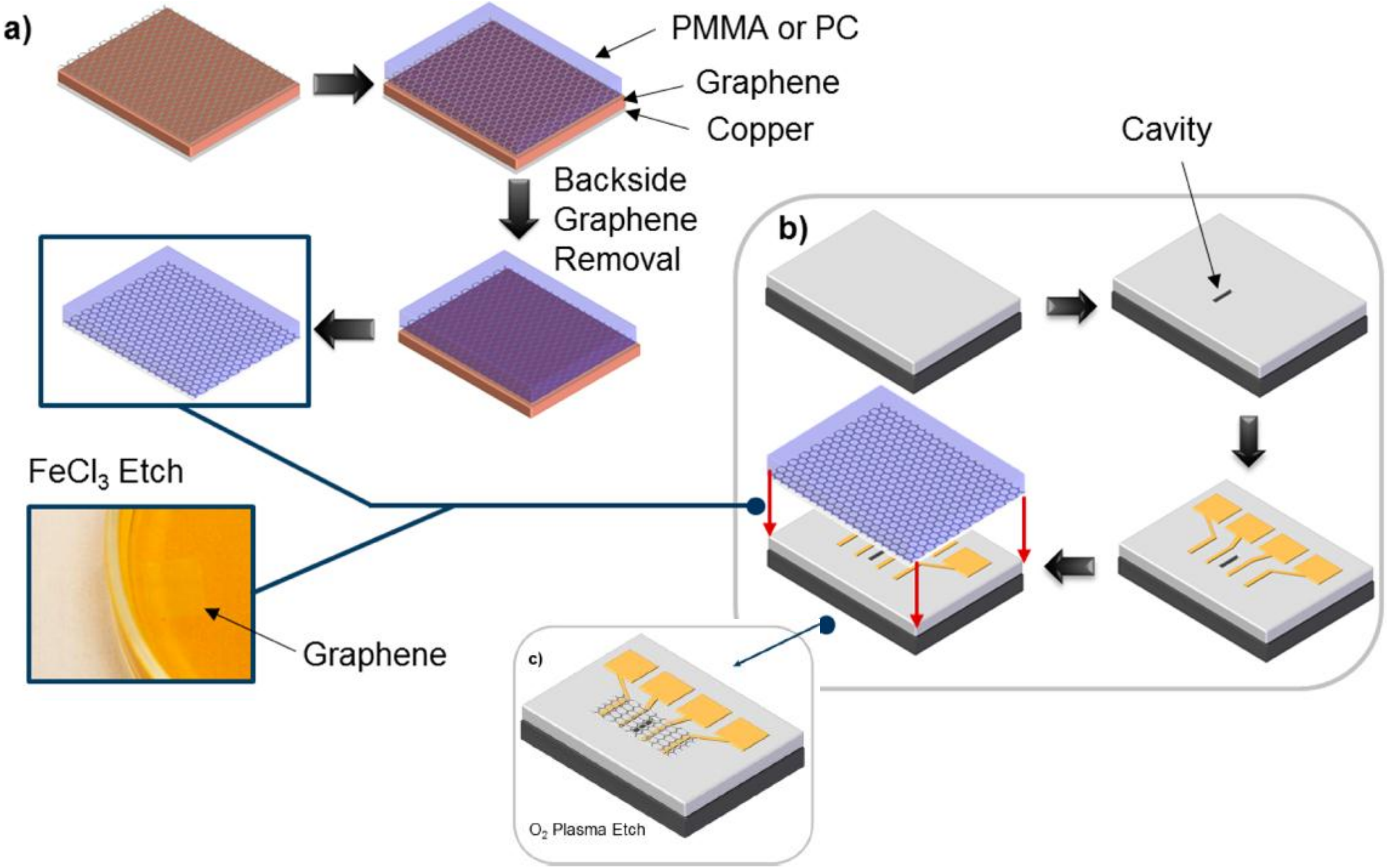


Schematic of Pressure Sensor



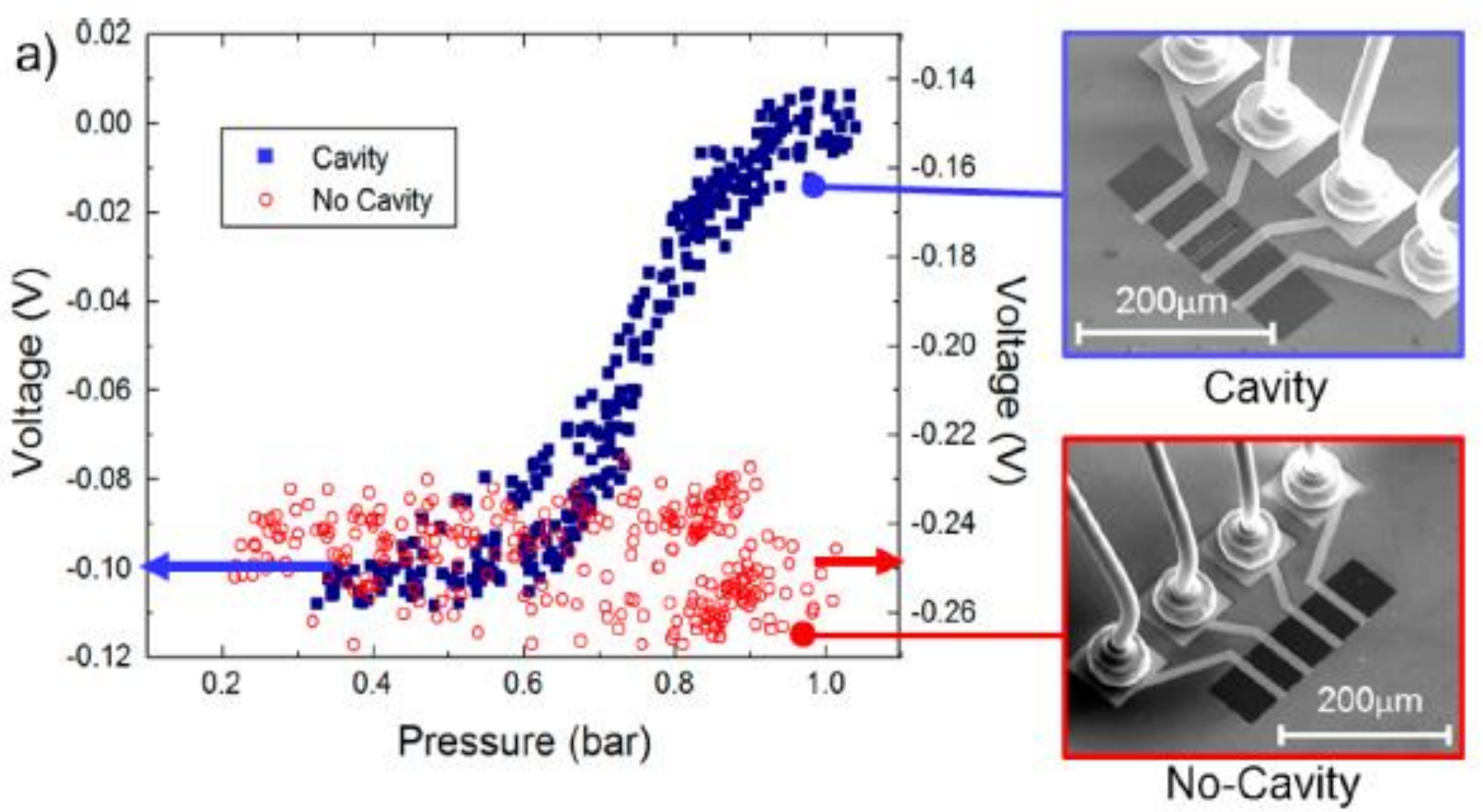
Smith, A. D., Niklaus, F., Paussa, A., Vaziri, S., Fischer, A. C., Sterner, M., ... & Ostling, M. (2013). Electromechanical piezoresistive sensing in suspended graphene membranes. *Nano letters*, *13*(7), 3237-3242.

Graphene-Integration in NEMS



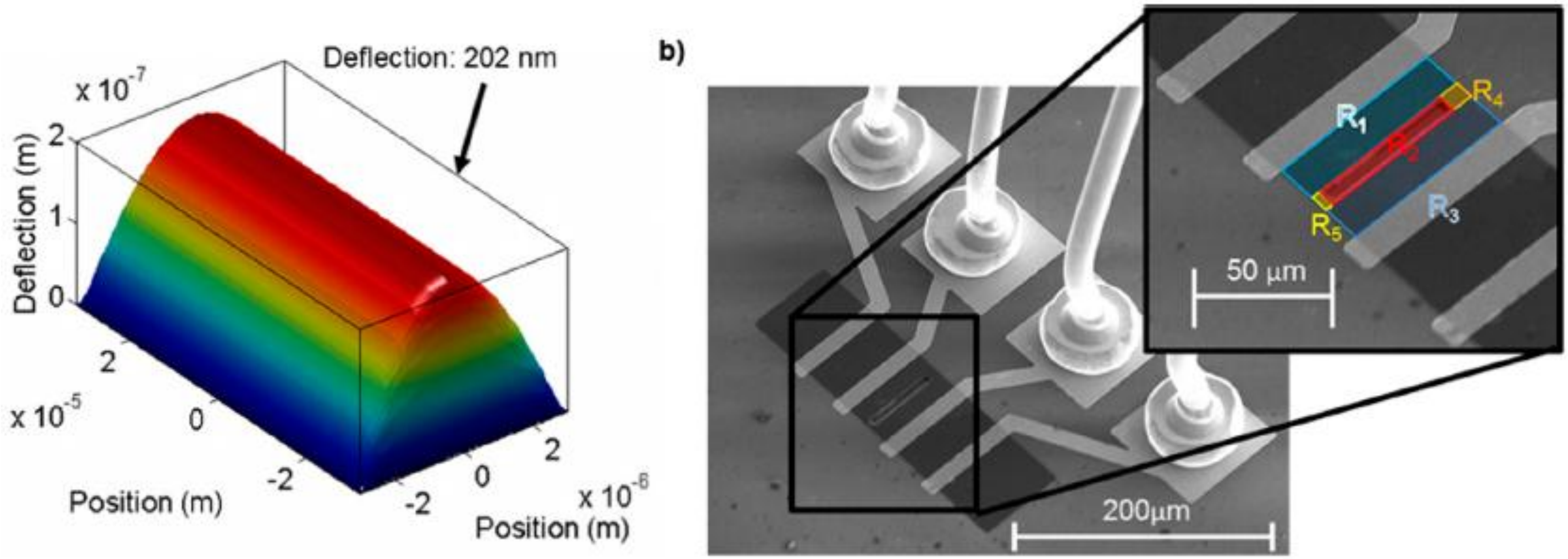
Smith, A. D., Niklaus, F., Paussa, A., Vaziri, S., Fischer, A. C., Sterner, M., ... & Ostling, M. (2013). Electromechanical piezoresistive sensing in suspended graphene membranes. *Nano letters*, *13*(7), 3237-3242.

Graphene-NEMS Pressure Sensing



Smith, A. D., Niklaus, F., Paussa, A., Vaziri, S., Fischer, A. C., Sterner, M., ... & Ostling, M. (2013). Electromechanical piezoresistive sensing in suspended graphene membranes. *Nano letters*, *13*(7), 3237-3242.

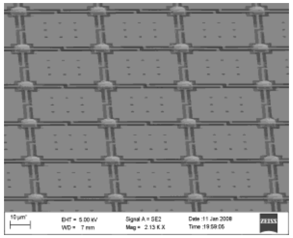
Graphene-NEMS Pressure Sensing

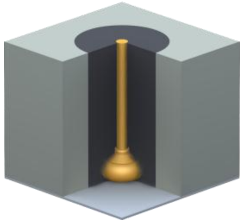


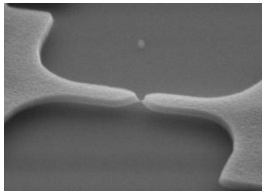
Smith, A. D., Niklaus, F., Paussa, A., Vaziri, S., Fischer, A. C., Sterner, M., ... & Ostling, M. (2013). Electromechanical piezoresistive sensing in suspended graphene membranes. *Nano letters*, *13*(7), 3237-3242.

Summary

- Heterogeneous 3D integration platform for micro-mirrors, IR bolometers and NEMS relays.
- Wafer-level vacuum packaging, and wire bonding and magnetic assembly for wire integration in MEMS.
- Graphene NEMS pressure sensors and nanofabrication technologies for tunnelling junctions.







Acknowledgements

Funding Sources

European Commission

erc European Research Council

HORIZON 2020

SEVENTH FRAMEWORK PROGRAMME

EUREKA innovation across borders

STIFTELSEN för STRATEGISK FORSKNING

VETENSKAPSRÅDET THE SWEDISH RESEARCH COUNCIL

Knut och Alice Wallenbergs Stiftelse

VINNOVA

Collaboration Partners

SenseAir

MICRONIC MYDATA

IBM

ST

silex MICROSYSTEMS

X-FAB MIXED-SIGNAL FOUNDRY EXPERTS

imec

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

University of BRISTOL

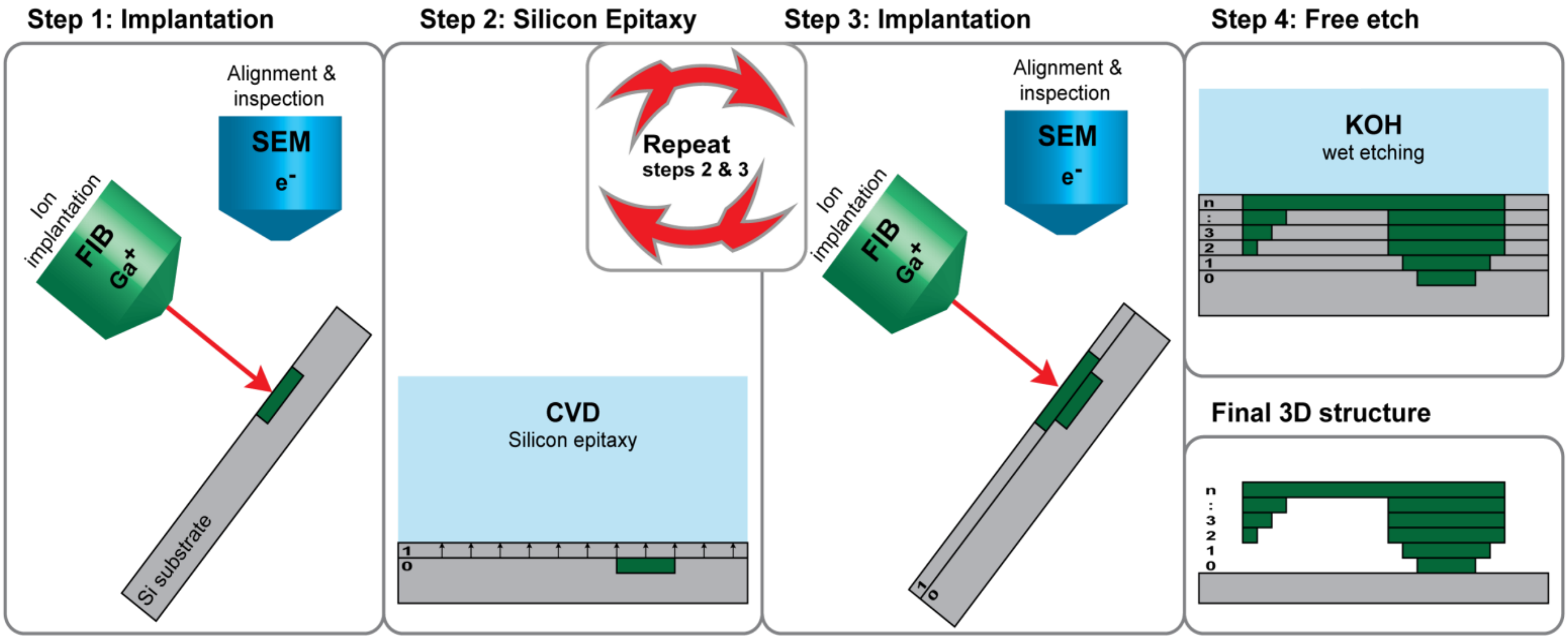
RWTH AACHEN UNIVERSITY

UNIVERSITY OF TAMPERE

VE RI TAS HARVARD

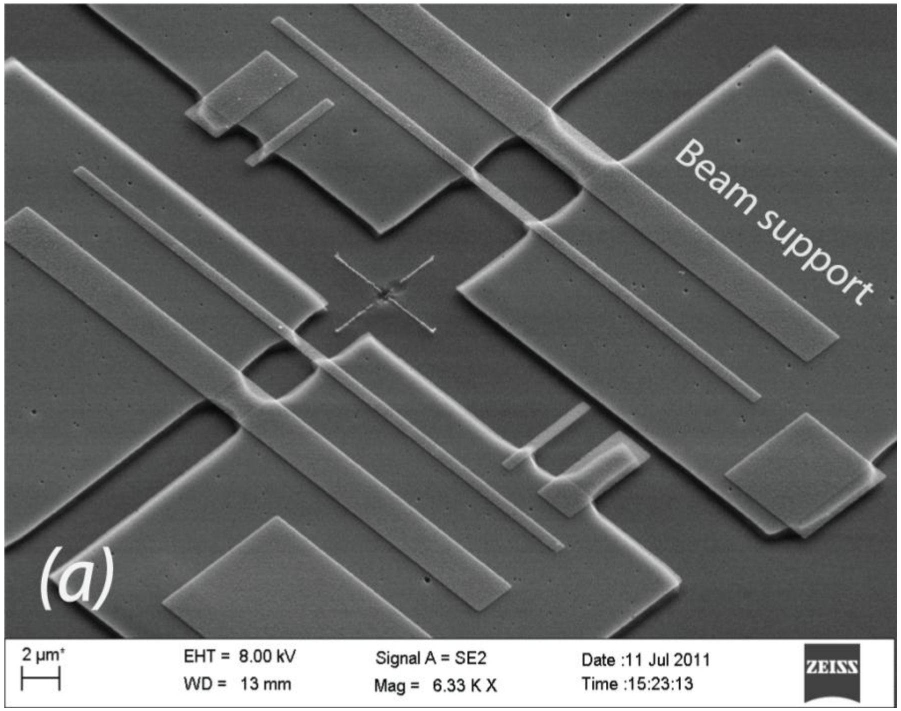
AMO

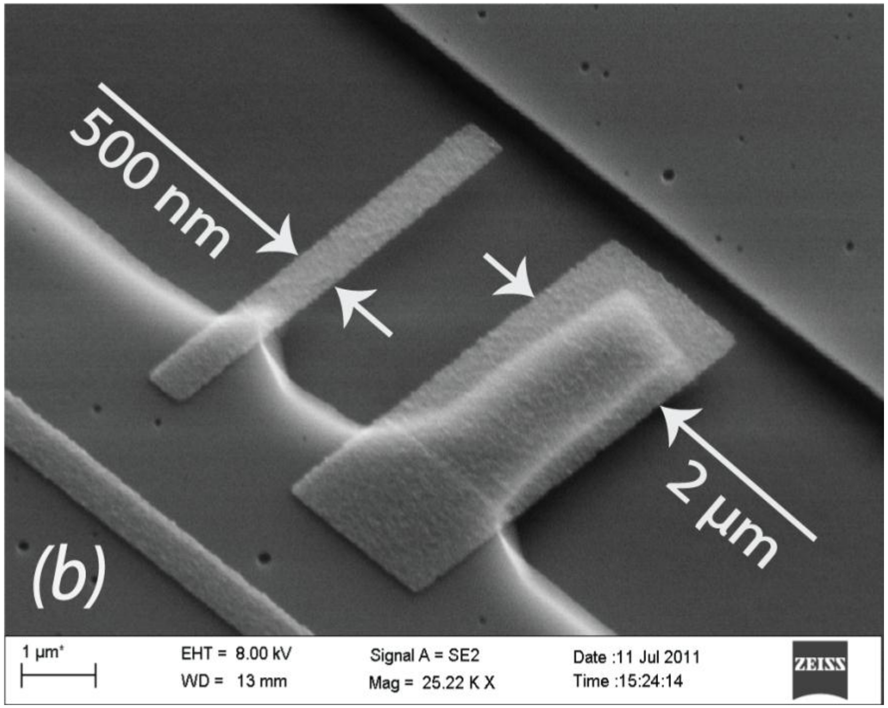
3D Printing Process for Si Nano Devices



A.C. Fischer et al., Advanced Functional Materials, 2012.

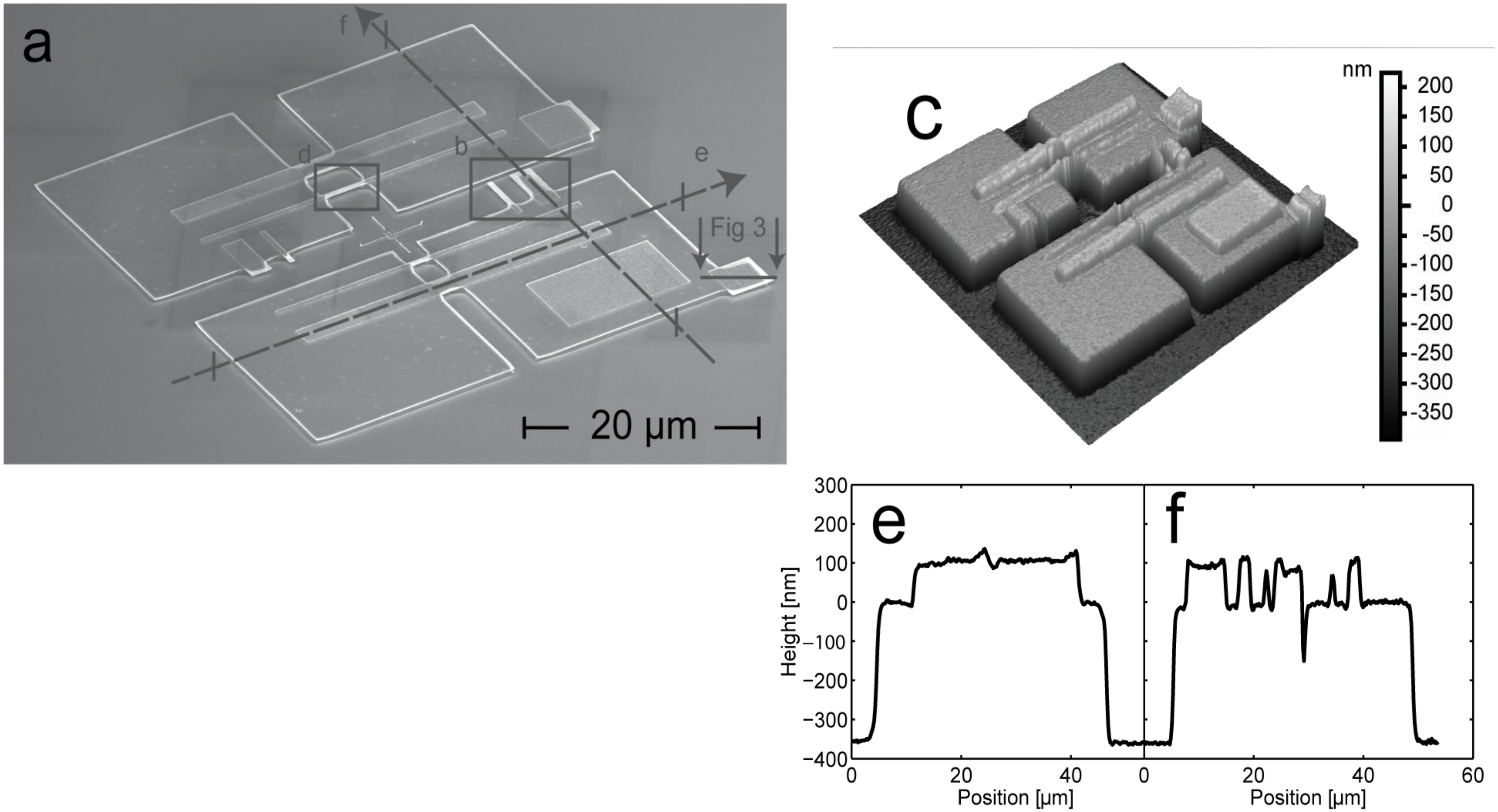
3D Printing of Si Micro and Nano Devices





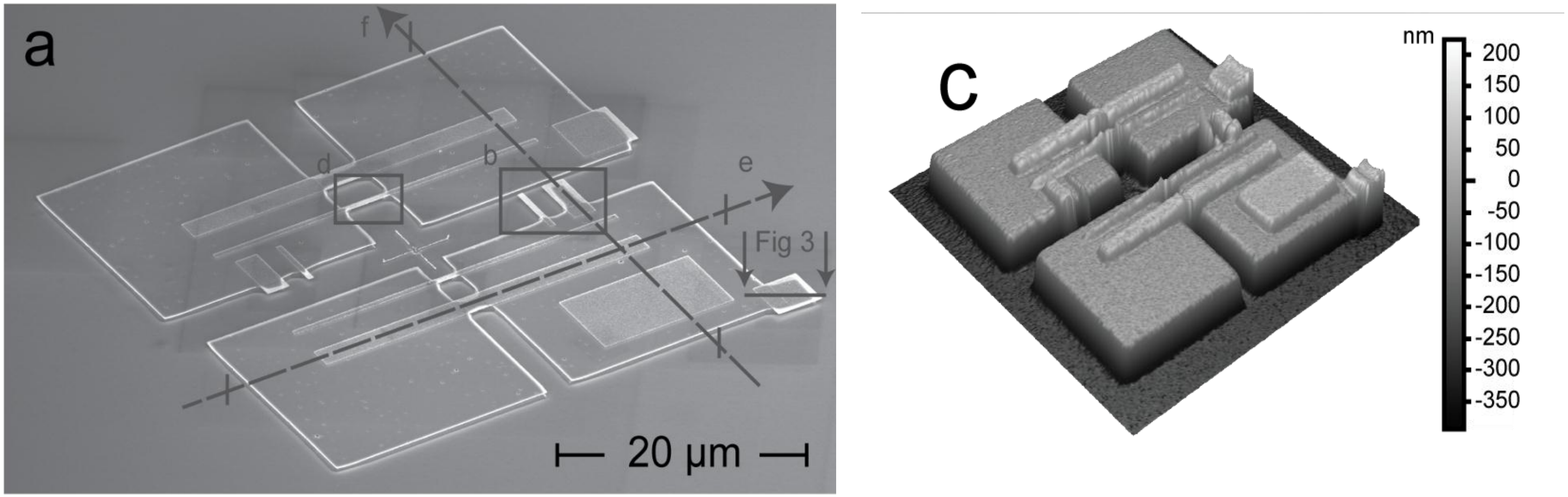
A.C. Fischer et al., Advanced Functional Materials, 2012

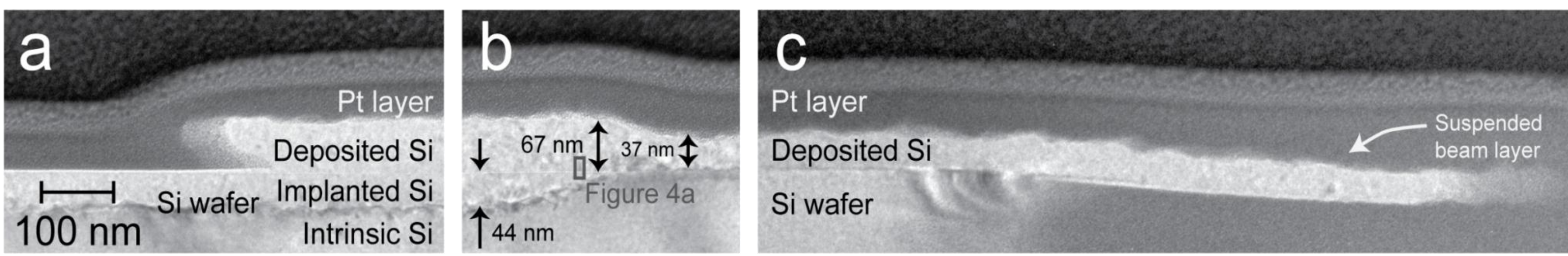
3D Printing of Si Micro and Nano Devices



A.C. Fischer et al., Advanced Functional Materials, 2012

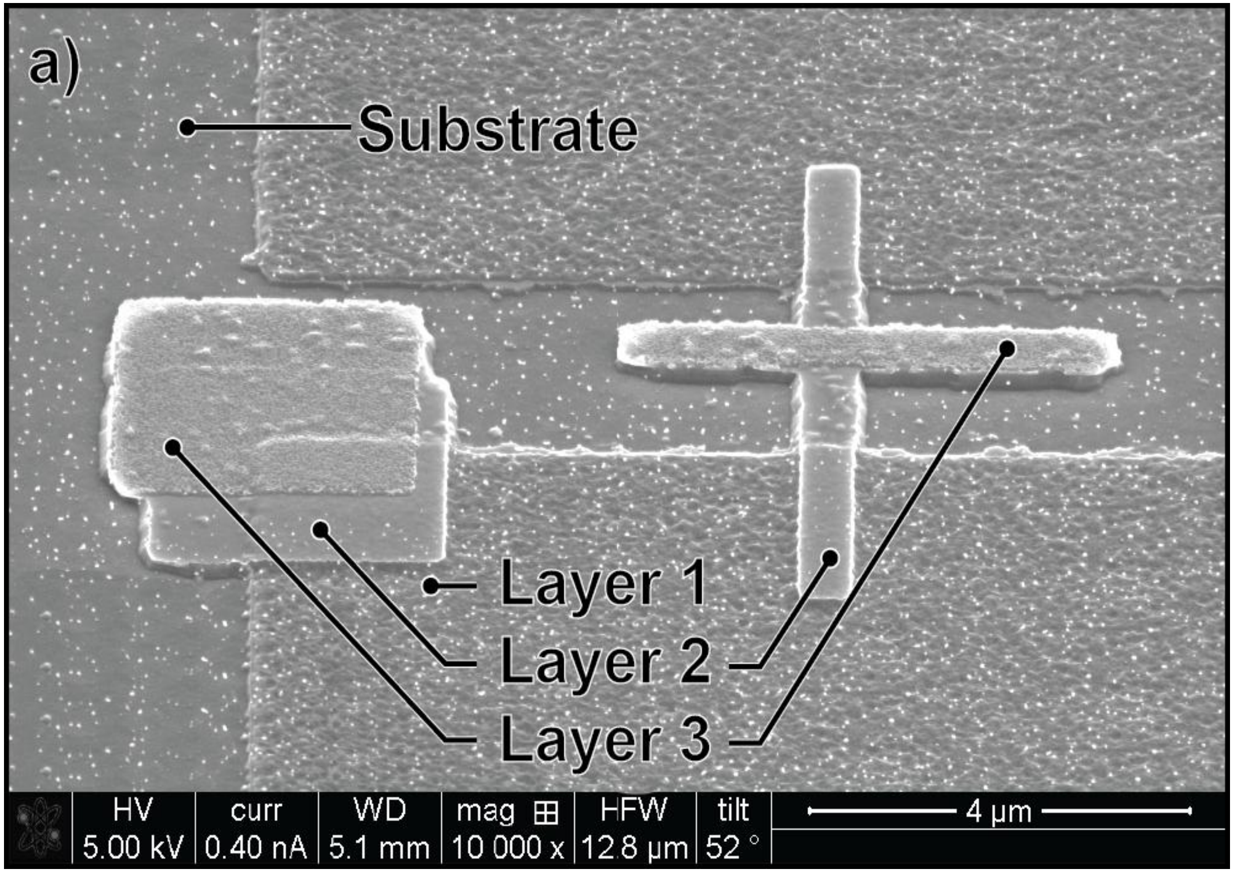
Cross Section of Si Nano Devices



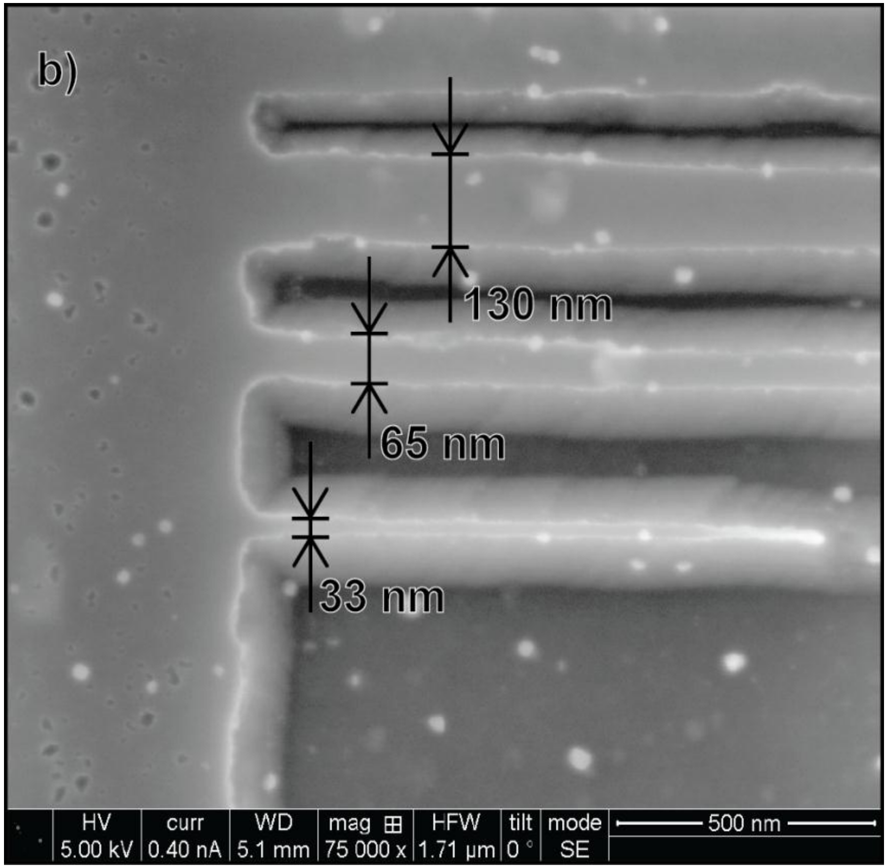


A.C. Fischer et al., Advanced Functional Materials, 2012

3-Layer 3D Printed Si Micro-Structures



Resolution Limits of 3D Si Printed Nano-Structures



- Line-width resolution of 33 nm demonstrated.
- Line-width resolution of 20 nm with FIB writing, reported in literature.
- Layer thickness on the order of 35-70 nm.

A.C. Fischer et al., Advanced Functional Materials, 2012